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25 YEARS OF EXCELLENCE IN ARMY SCIENCE AND TECHNOLOGY

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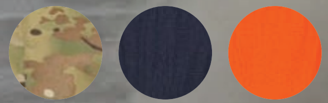

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Protection against biological and viral threats	Yes	Limited
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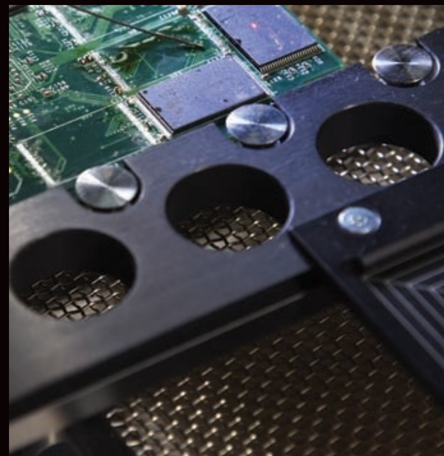
CB protection after exposure to wet sweat and other Battlefield Contaminates (BFC's)	Yes	Limited
Multiple wears prior to exposure	Yes	Yes
Protection Against Traditional Chemical Warfare Agents (GD/HD), 10gm challenge density	Yes	Yes
THIRD PARTY SPECIFICATIONS		
NFPA 1994 Class 3	Yes	No



DEPARTMENT OF THE ARMY
US ARMY RESEARCH, DEVELOPMENT AND ENGINEERING COMMAND
ARMY RESEARCH LABORATORY
2800 POWDER MILL ROAD
ADELPHI MD 20783-1138

Dear ARL Family

What an exciting time to be the director of such a stellar group as the U.S. Army Research Laboratory (ARL) achieves 25 years of excellence in science and technology in serving the Warfighter! In recognition of our work to address an ever-growing list of objectives in support of the Army and the Warfighter, the Defense Science Board this year has cited ARL as a Department of Defense innovation exemplar. Thanks and congratulations go to the whole ARL family.

As the fifth director of ARL, I'm privileged to oversee the lab leading in science and technological innovations to ensure our Warfighters have decisive overmatch on the field, and particularly to oversee ARL applying that same innovation to ourselves so we can have even more decisive overmatch in science and technology.

To that end, part of ARL's Research, Management and Leadership Strategy (RMLS) is to put our people first: to support them in their work/life balance, increase productivity, continue their learning, and enable collaboration at all levels and areas of ARL and with the S&T community.

Two years ago, our goal in adopting the RMLS was to make a good workplace even better. Now in our 25th anniversary year, my assessment is that ARL has now gone from a good place to work to a great place to work. That credit goes to you all. I want to thank my colleagues at ARL for their dedication to accomplishing ARL's missions for the past 25 years and their readiness to tackle the next 25 years of innovation to advance and safeguard the future of the United States of America.

Happy 25th anniversary, Army Research Laboratory.

Sincerely,

PHILIP PERCONTI
Director

DEPARTMENT OF THE ARMY
US ARMY RESEARCH, DEVELOPMENT AND ENGINEERING COMMAND
ARMY RESEARCH LABORATORY
2800 POWDER MILL ROAD
ADELPHI MD 20783-1138

Dear ARL Family:

For the last few years, it has been my distinct honor and privilege to serve as the military deputy of the U.S. Army Research Laboratory (ARL).

ARL's mission has always been to support the Warfighter. I take personal pride both in having led Warfighter teams in the past, and now in representing the Warfighter to ARL's team missions to evaluate the present and future needs of today's Warfighter.

In today's Army, as ever, the Warfighter is at the end of a long supply chain which starts in the cutting-edge scientific and technological research coming from the dedicated teams of ARL.

That supply chain takes a few more steps through ARL as its teams focus on turning today's lab innovations to practical applications.

The diverse scientific and technological disciplines and expertise shown by ARL's staff allows ARL to create multifaceted, carefully tested solutions to best meet our warriors' needs and gaps. Such heightened focus on this end of the supply chain serves to best enhance our Warfighters' capabilities and success in their missions, both on the battlefield and off.

Congratulations to ARL, and my best wishes on your continued success.

Sincerely,

Kevin L. Ellison

Kevin L. Ellison, Colonel, U.S. Army
Military Deputy, ARL

COMMANDING GENERAL
10^{TH} MOUNTAIN DIVISION (LIGHT INFANTRY) AND FORT DRUM
FORT DRUM, NEW YORK 13602-5007

June 27, 2017

On the Occasion of Army Research Laboratory's 25^{th} Anniversary

To the ARL Family,

I am delighted to congratulate the United States Army Research Laboratory on the milestone of 25 years of excellence in science and technology on behalf of the United States Army and the citizens we protect.

The world was a different place when I was a company commander in 1992 - when eight legacy labs converged to form the U.S. Army's sole corporate laboratory.

The Cold War just ended, and while we were continuing to analyze our role in the world, the ARL began a new era of innovation and set to work solving tomorrow's problems. Over the past quarter-century, the men and women of ARL have risen to the demands of a mission with vague parameters but a specific mission: the protection of the Warfighter. On behalf of the Soldiers you dedicate your brilliance, I thank and commend you.

As we confront enemies on multiple domains, I am proud that Army's corporate lab earned the distinction of being singled out by the Defense Science Board as a model of innovation.

It's easy to talk about innovation, but it's much harder to actually do it and make it relevant for soldiers. After meeting the brilliant people working at ARL and other labs and seeing what you produce, I know that your work saves lives.

Heartiest congratulations to the Amy's ARL Family from the Fort Drum Family.

Climb to Glory!

Walter E. Piatt
Major General, U.S. Army
Commanding

On the evening of September 30th, 1992 I participated in a farewell dinner – a dinner to bid farewell to the Army's Harry Diamond Laboratories which was almost 40 years old at that time. The next morning, the first day of Fiscal Year 1993, HDL along with six other of the Army's "independent" laboratories would be merged into what would be the Army's new "corporate laboratory" – The Army Research Laboratory – ARL, whose headquarters would be located at the former site of HDL in Adelphi, MD. And now we are celebrating ARL's 25th anniversary.

The intent in forming such a centralized laboratory organization was to bring together the Army's basic and applied research capabilities and promote their collaboration and cooperation in the generation of technology solutions to some of the most severe problems facing our forces on the battlefield. And as it turned out, because of the capabilities of the seven labs being joined together on that October 1st morning, and as a result of the inspired leadership of those labs now coming together into a single organization under the leadership of its first Director, the truly incredible Dr. John W. Lyons, ARL not only fulfilled its original mission, but carried it on in ways that we at the time could not even imagine.

Not only did the numerous products of the Lab's R&D endeavors end up in many operational situations at great benefit to our soldiers, but the very management of technology organizations and processes themselves were enormously enhanced by the very creative procedures and techniques that ARL developed in the process of doing the actual "bench work". ARL developed new and imaginative ways to develop and execute strategic approaches to its operations, new ways to evaluate and report its performance, new ways to join and partner with its stakeholders and with the private commercial and academic sectors. It rapidly became recognized as a truly "world class" research laboratory.

And so we now celebrate that 25-year landmark. ARL has evolved and matured over the years. It has developed further in several dimensions – technological, managerial, personnel, etc. It has moved into new technology areas of importance to the Army. I look upon the Lab today with enormous pride at what it has accomplished and what it has become, and I truly believe that it will continue that upward course over the next 25 years.

Happy Birthday to ARL, and my heartiest congratulations to all the members of the ARL family, past and present.

DRED

Dr. Edward A. Brown

October 2, 2017

U.S. Army Research Laboratory
2800 Powdermill Road
Adelphi, MD 20783

To the innovators at ARL:

Congratulations to ARL on its 25th anniversary.

ARL's mission to innovate in science and technology resonates with me. But ARL's focus on transitioning that knowledge to the real world is the key, as it is at my agency, part of USAID, where turning science and innovation into action is the only way to reach our ultimate goal of accelerating the end of extreme poverty.

I was delighted to speak to ARL's innovators at the end of March. I believe that innovation grows with a full exchange of ideas among a diverse group of contributors. The ARL team impressed me with the breadth of scientific and technical fields represented and their eagerness to collaborate on how to develop and maintain a rapid pace of innovation for ARL as a whole. I am delighted to celebrate #ARL25 with such an outstanding team.

Very truly yours,

Alexis Bonnell

October 23, 2017

U.S. Army Research Laboratory
2800 Powder Mill Road
Adelphi, MD 20783

To my friends at ARL:

Congratulations to ARL on its 25th anniversary.

ARL's stated mission is to innovate in science and technology, and to transition that knowledge to the real world. No wonder, then, that ARL has drawn an outstanding group of bright and talented people, covering a broad range of scientific and technical fields, to collaborate to achieve that mission. I was delighted to have had the opportunity to speak to your staff in April. ARL's warm welcome, and the robust, collaborative, and insightful interchange of ideas we enjoyed, made me proud to join a group of fellow #ChangeAgents to celebrate #ARL25.

Heartiest congratulations and here's to continued exponential innovation and success. Onward and upward, together!

Sincerely,

David A. Bray
Executive Director
People Centered Internet and U.S. Eisenhower Fellow

VETERANS' EMPLOYMENT AND TRAINING SERVICE
UNITED STATES DEPARTMENT OF LABOR

September 6, 2017

U.S. Army Research Laboratory
2800 Powder Mill Road
Adelphi, MD 20783

To ARL:

Congratulations on 25 years of service and excellence in science and technology.

As a veteran of the United States Army, I recognize the value of ARL's many contributions to innovation in science and technology for the Warfighter and how valuable those innovations have been in real world situations facing our soldiers at home and abroad.

I was delighted to be invited to speak as part of the **#ARL25** series, particularly on the importance of keeping ARL a great place to work. As the proud mother of a high school STEM student who participated in the summer GEMs program that ARL sponsors, I have some insight into the brilliance and creativity that your staff brings to their jobs. That kind of enthusiasm can't be faked; today's kids would spot a false note in a heartbeat. It speaks volumes about ARL as an employer that has left a lasting impression upon my daughter and others in the GEMs program who have been inspired to continue in STEM fields after seeing what ARL's bright and creative people do in carrying out their important mission. That enthusiasm is a large part of what keeps current staff and will draw future scientists to ARL and makes it a great place to work, now and for years to come.

You have my heartfelt congratulations. Here's to the next 25 years – and then some!

Sincerely,

Mika J. Cross

September 6, 2017

On the Occasion of Army Research Laboratory's 25thAnniversary

To the ARL Family,

Congratulations on your 25 years of excellence in science and technology. It was an honor to be chosen for the ARL25 Guest Speaker Series commemorating the crucial work being done here today defining strategic thought as we collectively move forward.

My work on long-term global trend assessments, urbanization, and exponential technologies and their impact upon the global community lead me to appreciate the growing cohort of scientists, strategic thinkers and military professionals who form the base of this lab – divining geopolitical issues and appropriate responses to them that ARL addresses in a multitude of ways.

ARL's innovative, collaborative approach creates the cross-pollination necessary to forecast into the future. I applaud ARL for creating knowledge-sharing forums spanning diverse skill sets recognizing that most problems are require multidimensional approaches to understanding as well as multidiscipline solutions.

Emerging global challenges require Innovative approaches such as those developed at ARL. Your team has earned the right to be proud of their accomplishments.

Congratulations to all the people in the ARL family. I was pleased to be part of this important celebration.

Cordially,

Banning Garrett, PhD
Faculty, Singularity University
Senior Fellow, Global Confederation of Competitiveness Councils

October 16, 2017

Congratulations to Army Research Lab on 25 years of excellence in science and technology that has saved lives across the DoD. As a Navy Admiral, I can attest first-hand to ARL's dependability and impact at the point of need.

For example:

1. Non DoD industry is developing technology that can outperform any DoD technology - driverless car and truck technology are examples of work I believe ARL is leading. This will support both the Army and Marine Corps and save lives.
2. DoD has to figure out how to harvest that tech base without adding huge cost multipliers – and ARL will be key in evaluation of what fits with DOD and what does not.
3. Cyber offense and defense is here to stay and must be included in the design space – As it has done in the past, ARL will help define where and how Army should lead in developing multi-domain capabilities for the war fighter.
4. More cheaper disposable systems may be significantly better than one expensive bullet – It will be a combination of ARL and Navy Labs which will help develop systems like Rail Gun and energy weapons to reduce the cost of our munitions and put DoD on the correct side of the cost equation.

ARL well-deserves the Defense Science Board's honor as Army's "Innovation Exemplar."

ARL's long history of collaboration with other DoD branches and public, private and NGO partnerships forecasts the important role ARL will play to ensure near, mid, and long term, decisive overmatch.

Finally, my own company LRI is doing research in logistics and cyber that can help and we hope to continue our collaboration with ARL.

LMI appreciates the increasingly vital role ARL plays in equipping our future force throughout the Army and across the DoD.

I am delighted to extend my heartiest congratulations to Dr. Perconti, COL Ellison, MSG Taylor, and the entire ARL S&T and staff. As we say in the Navy BRAVO ZULU for a job Well Done.

Sinclair M. Harris
RADM USN (Retired)
Vice President, Defense Market, LMI

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James L. Hodge
President

October 17, 2017

On the Occasion of the Army Research Laboratory's 25th Anniversary

To the entire Army Research Laboratory team,

On behalf of everyone at the Institute for Defense and Business, I would like to offer my most sincere congratulations to the Army Research Laboratory for 25 years of steadfast excellence in Science and Technology.

The results of your efforts to support our Warfighters have been astounding. Cutting edge research and innovation have been engrained in your culture and year after year, our Soldiers have reaped the benefits. Additionally, it's clear that the United States Army would not be in position to dominate the Multi-Domain battlefield of the future if not for your research. You have been the driving force behind bringing the Army into the 21st century, preparing us to fight not only by land, air, sea, and space, but also in cyberspace and across the electromagnetic spectrum.

Your continued research endeavors to protect the future force are vital to the Army's continued relevance and success and by operating on a 50 year horizon, ARL will be in position to assist and protect Warfighters for generations to come.

Once again, please accept my congratulations to the Army Research Laboratory on 25 years of excellence in Science and Technology.

Sincerely,

James L. Hodge, MG (USA Retired)

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October 15, 2017

U.S. Army Research Laboratory
2800 Powder Mill Road
Adelphi, MD 20183

To the ARL Family:

It is with great pleasure that c6 Strategies LLC extends our warmest congratulations to ARL on your 25th anniversary.

For the past 25 years, the Army Research Lab has provided cutting edge innovation to serve our nation's defense and national security. Your work ensures that the United States warfighter is smarter, stronger, faster and safer. ARL continues to expand in order to meet the needs of our forces as they face constantly evolving threats. You have demonstrated time and time again your dedication as well as the sheer visionary brilliance of the men and women who serve the ARL mission.

We thank you, ARL, for thinking ahead to develop revolutionary solutions for a world that does not even exist yet. This work will enable the U.S. warfighter to meet the challenges of the future threats they will face. We trust and rely on you for much-needed future advances which will continue to SAVE LIVES.

Twenty-five years in technology research and development for our U.S. Army is an incredible accomplishment. Here's to the pioneering and cutting-edge advancements of ARL for the next 25 years and beyond!

Respectfully,

Dana W. Hudson
CEO
c6 Strategies LLC


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October 17, 2017

U.S. Army Research Laboratory
2800 Powder Mill Road
Adelphi, MD 20783

To U.S. Army Research Laboratory:

I was delighted to have had the opportunity this year to speak to ARL staff about a topic dear to my heart. Breaking through the status quo to achieve true innovation, not just today but tomorrow and the days after that, is the key to meaningfully creative work and success in today's ever-changing world. That ARL fosters the spirit of innovation in its culture and in each individual staff, provides me with an even greater appreciation for your contribution to the world and speaks to the success of ARL.

Again, congratulations, and here's to continued innovation!

Jump on 2,

Tamara Kleinberg
Founder & Innovation Enabler, LaunchStreet

SAL Security Awareness Lab

October 1, 2017

Dr. Philip Perconti, Director
Army Research Laboratories
Adelphi, MD 20783

Dear Dr. Perconti,

I'm excited to congratulate the Army Research Laboratories on your twenty-five years of innovation to support the American warfighter. As an academic who chose to enter the field of national and homeland security policy, I have a deep appreciation for the role of research in supporting our men and women in uniform. But it takes more than research. It takes the kind of "translation" that ARL is known for that can bring innovations from the lab to the frontlines.

I was honored to have an opportunity to speak at ARL this past July during your anniversary speaker series. The experience was a thoroughly welcoming one for me, and it was gratifying to see the interesting array of research on human factors and cybersecurity taking place at ARL.

As the challenges for the Army change in a new era of conflict, the importance of ARL and its mission has never been greater. I wish you well for the future as you tackle the next set of challenges over the horizon.

Sincerely,

Dr. Gregory Michaelidis

SHPE
Society of Hispanic
Professional Engineers

13181 Crossroads Parkway North Suite 450
City of Industry, CA 91746-3497
323-723-3970 Office
323-725-0316 Fax

October 12, 2017

U.S. Army Research Laboratory
2800 Powdermill Road
Adelphi, MD 20783

To U.S. Army Research Laboratory:

Congratulations on your 25th anniversary! Twenty-five years is an amazing milestone in these days of rapid change.

I was very happy to have been invited to speak at ARL to celebrate both ARL's anniversary and national Hispanic Heritage Month. This combination of missions echoes my dual mission at the Society of Hispanic Professional Engineers, which is to empower the Hispanic community to realize their fullest potential and to impact the world through STEM awareness, access, support and development.

I commend ARL on its successful pursuit of innovation by embracing carefully calculated risks that foster advances in STEM fields, and I am delighted to contribute to ARL's long history of innovation through the diversity of its staff and S&T teams.

My deepest congratulations on #ARL25, and here's to continued success.

Sincerely,

Raquel Tamez
Chief Executive Officer

SHPE changes lives by empowering the Hispanic community to realize its fullest potential and to impact the world through STEM awareness, access, support and development.

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A HISTORY OF SUCCESS AND A FUTURE OF PROMISE

By Jenna Brady, ARL Public Affairs and ARL25 Program Manager

Richelle Mead once said, “History is important because it teaches us about the past. And by learning about the past, you come to understand the present, so that you may make educated decisions about the future.”

The U.S. Army Research Laboratory (ARL) is the Army’s corporate research laboratory, with the mission to discover, innovate and transition science and technology to ensure dominant strategic land power.

While turning 25 this year, ARL has a rich history in the development of innovative science and technology solutions for the Warfighter.

In October 1992, ARL was activated, growing out of the Base Realignment and Closure process, the LAB 21 study and other evaluations.

The new lab consolidated seven laboratories belonging to the Army Materiel Command and their antecedents in the Technical Corps with other Army research elements including the Army Research Office, which officially became part of ARL in 1999, to form a centralized laboratory concentrating on scientific research, technology development, and analysis.

ARL’s predecessor labs include Harry Diamond Laboratories, the Ballistic Research Laboratory, the Electronic Technology and Devices Laboratory, the Human Engineering Laboratory, the Atmospheric Sciences Laboratory, the Vulnerability Assessment Laboratory, and the Army Material Technology Laboratory.

Among their many successes, individuals in these labs helped develop world-changing technologies such as the proximity fuze; the Electronic Numerical Integrator and Computer (ENIAC), the first operational, general purpose, electronic digital computer; and grew some of the first synthetic large quartz crystals.

In its early years, ARL was involved in significant projects that would lead to the development of revolutionary technologies for an ever-changing fighting force for which the lab is known today.

ARL PHOTO

The U.S. Army Research Laboratory at Adelphi, Maryland.


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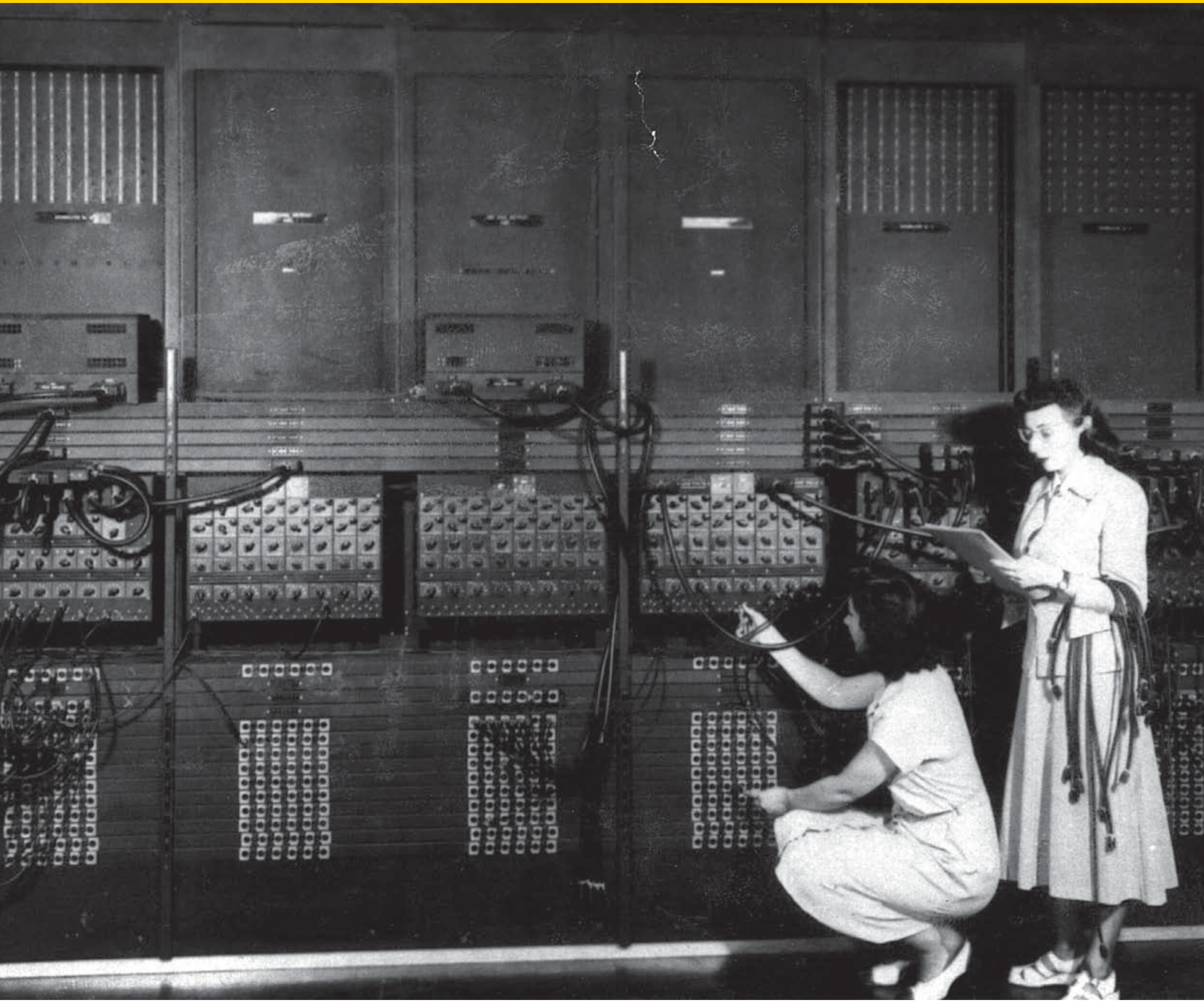


U.S. ARMY PHOTO FROM THE ARCHIVES OF THE ARL TECHNICAL LIBRARY

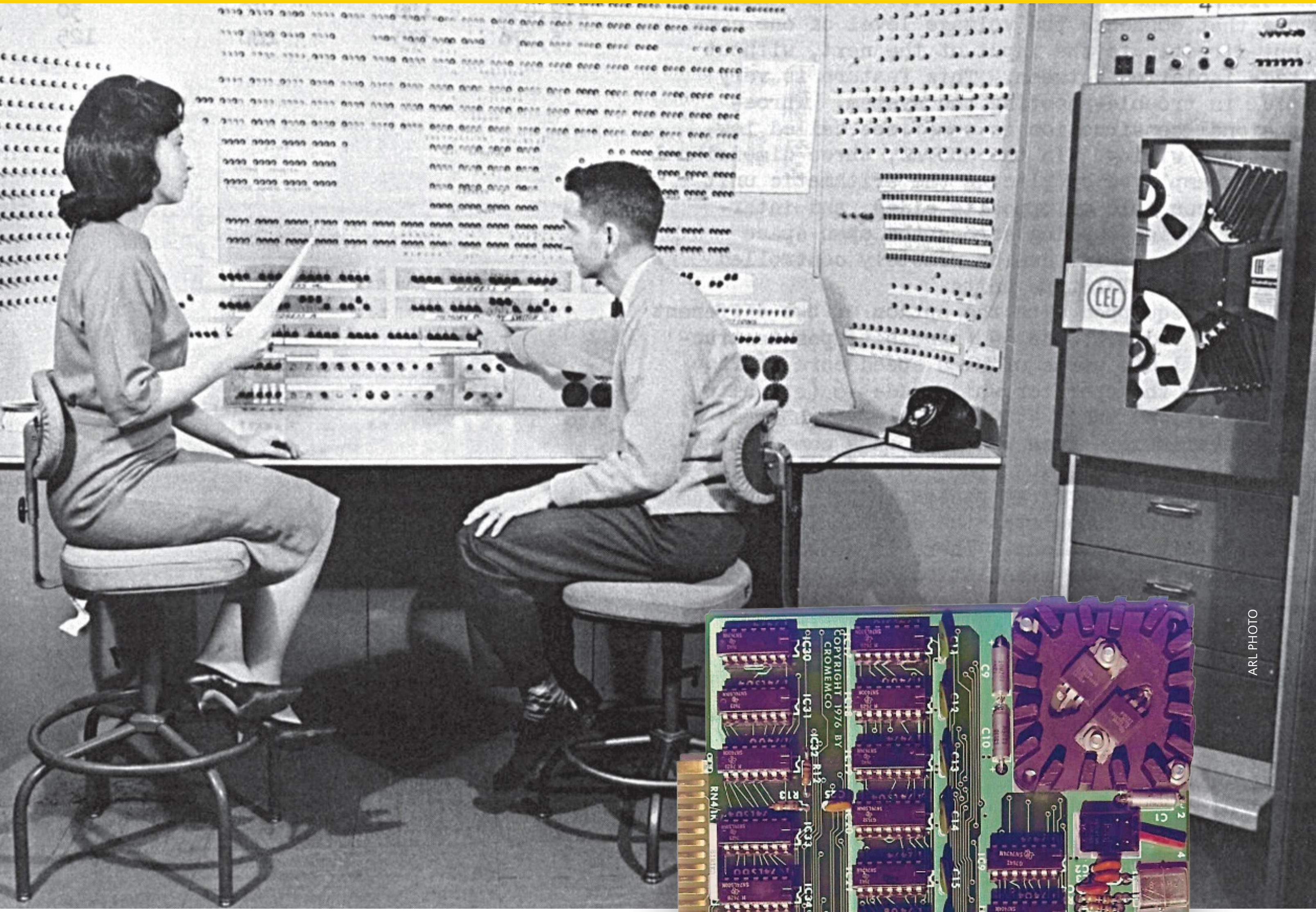
The world's first operational, general purpose, electronic digital computer, the Electronic Numerical Integrator and Computer (ENIAC) was developed by the Ballistics Research Laboratory (BRL), one of the predecessor labs that later were folded into ARL. In this photo, two women are wiring the right side of the ENIAC with a new program.

Project areas included, but were not limited to, lightweight armor, robotics, smart munitions, novel lethal mechanisms, materials for vehicles, and protective materials for the Soldier.

Specifically, such projects include the Warrior's Edge program, which involved virtual reality simulation to identify the technology needs of individual Soldiers, and "Owning the Weather," a coordination of previously existing information systems to give friendly forces the ability to see, maneuver, fight, and win in all types of weather by providing commanders and staff with advance knowledge of battlefield environmental conditions and likely effects, enabling them to select the most appropriate mix of sensors, weapons systems, and tactics.

Other projects include the Battlefield Combat Identification System, which would better identify both enemy targets and allies in the field; ultra-wide band foliage penetrating synthetic-aperture radar to detect targets employing camouflage, concealment, and other deceptive techniques; the Commander's Visualization Research Tool, which promised to give commanders real-time formatted battle information; and the High-Capacity Artillery Projectile, which represented a major milestone toward the goal of substituting composites for steel in future shells, thus permitting the weight savings to be allocated to greater payload or longer range.

Currently, as an element of the U.S. Army Research, Development and Engineering Command, which is led by Maj. Gen.



ARL PHOTO

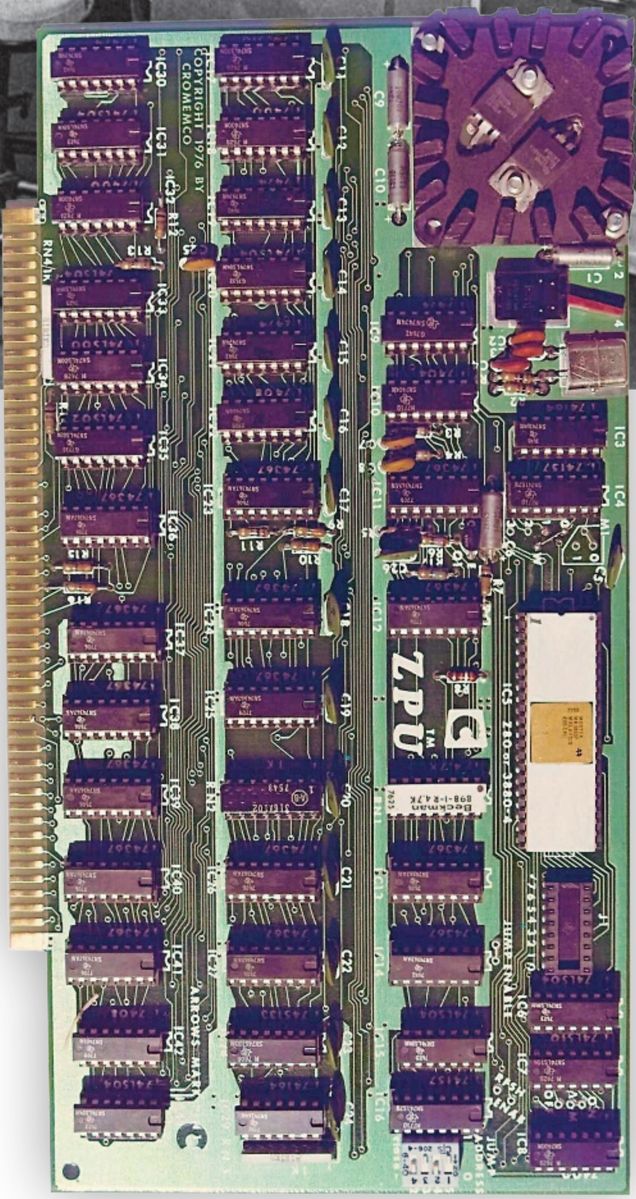


PHOTO COURTESY OF NIKKI CHILDRESS

ABOVE: Two Ballistics Research Laboratory (BRL) employees working with the BRLESC-I, which, in 1962, was the fastest computer in the world. The computer was built entirely by BRL engineers from standard parts that were developed at the then-National Bureau of Standards. BRL, which was located at Aberdeen Proving Ground, Maryland, was the center for the U.S. Army's research efforts in ballistics and vulnerability/lethality analysis. In 1992, BRL's mission, personnel, and facilities were incorporated into the newly created Army Research Laboratory, and BRL was disestablished.
RIGHT: The first Program Data Processor (PDP) 11/70 developed by Ballistics Research Laboratory (later to become a part of ARL) employees in the late 1970s. BRL played a significant role in the evolution of scientific computing architectures and technologies.

Cedric Wins, ARL's diverse team of more than 3,000 scientists, engineers, technicians, and military, administrative, and contractor personnel is pioneering cutting-edge technology for the protection of America's Soldiers, the defense of our citizens, our technical superiority as a global leader and standard-setter, and our military dominance.

More current technological successes ARL has under its belt include the Blow Torch Counter-IED System, a vehicle-mounted system that detonates improvised explosive devices at safe stand-

off distances; the M1114 Humvee Interim Fragmentation Kit 5, which was fielded as a ballistic protection improvement against small arms fire and fragments for the M1114 Humvee in April 2006 and has been bought in quantity as an upgrade since then; and Constant Hawk, a set of sensor systems that uses an electro-optic payload to collect intelligence and identify areas that require increased surveillance by other assets on the battlefield.

In World War II, proximity fuzes were used for targets such as planes, missiles, ships at sea and ground forces. A miniaturized Doppler radar provided a more sophisticated trigger mechanism than the common contact fuze or timed fuze, making the ammunition five to 10 times more effective. Years before the Army's laboratories came together, the organizations that make up ARL had successes of their own, to include helping to develop this fuze with greater firepower and better accuracy.

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■ **Constant Hawk, flown aboard C-23 and MC-12 aircraft (shown here) employed a set of sensor systems using an electro-optic payload to collect intelligence and identify areas that require increased surveillance by other assets on the battlefield. It was especially useful for identifying probable IED sites.**

DOD PHOTO BY STAFF SGT. TIFFANY TROJCA

As part of its strategy, ARL focuses on nine essential research areas: Human Agent Teaming, Artificial Intelligence and Machine Learning, Cyber and Electromagnetic Technologies for Complex Environments, Distributed and Cooperative Engagement, Tactical Unit Energy Independence, Manipulating the Physics of Failure for Robust Performance of Materials, the Science for Manufacturing at Point of Need, and Discovery.

ARL organizes this work into eight technical campaigns that address an expanse of issues: Human Sciences, Information Sciences, Sciences for Maneuver, Sciences for Lethality and Protection, Materials Research, Computational Sciences, Assessment and Analysis, and Extramural Basic Research.

In addition, the laboratory continues to partner with leading researchers in industry, academia, and small business through initiatives such as Open Campus and cooperative programs, while also reaching out to the active Army to ensure that programs produce advanced technologies that support Soldiers in the field today – and will continue to do so in the future.

Examples of additional innovative ARL programs and facilities include:

- Network Science Research Laboratory: The first of ARL's Open Campus spaces, this state-of-the-art facility is dedicated to exploring network science challenges with in-person research collaboration.
- IP Store: Available to the public, ARL's online intellectual property store enables visitors to browse, research, and apply for a license to make, use, and sell patented technology from ARL at favorable, pre-negotiated terms. The laboratory has about 380 issued patents in its portfolio covering 14 different technology categories.
- ARL Centers: ARL is reversing the 1990s consolidation trend and establishing new sites across the country where new technologies are being developed, attracting a local talent pool from major universities. ARL West was established in Los Angeles to tap into leading work on interaction between humans and information. ARL South, in Texas, opened in 2016, and additional centers are planned.
- Sabbaticals: To increase ARL's "surface area" with external partners, ARL encourages sabbaticals for staff members

U.S. ARMY PHOTO BY MASTER SGT. ERICK RITTERBY

who are in close contact with academic researchers on the cutting edge of turning science into technology. Returning scientists bring new insights and perspectives into the lab.

- Scientific Services Program: An accelerated contract mechanism enables federal government organizations to obtain specialized scientific and technical services to accomplish organizational goals and mission objectives related to research and development.

"ARL is proud to celebrate a quarter-century of empowering, unburdening, and protecting Soldiers by honoring the brilliant men and women who paved the way, and to recognize the diverse talents of thousands of people within ARL who give their all every day," said ARL Director Dr. Philip Perconti. "As the Army's corporate research laboratory, ARL is always focused on the future. We're excited to embark on a new era of discovery, invention, and collaboration with government, universities, and private-sector partnerships that will continue to drive our success for the next 25 years and beyond."

Through historical triumphs and lessons learned, present invigoration and superior skillsets, and a future of promising enhanced capabilities for the Warfighter, ARL stands proud as a team that is prepared to face whatever challenges lie ahead, as those challenges, and how the able men and women of ARL approach them, are what makes the lab a premier organization that has the ability to stand the test of time. ■

■ **ARL also developed the Battlefield Combat Identification System, employed on platforms such as the M1A2 Abrams, which would better identify both enemy targets and allies in the field.**

U.S. Army Pacific Soldiers of the 25th Infantry Division view video feed from a Phantom 4 (UAS) quadcopter during the Pacific Manned-Unmanned Initiative July 22, 2016, at Marine Corps Training Area Bellows, Hawaii. Among the solutions to tactical challenges facing the Army in future multi-domain operations are non-human agents such as unmanned airborne and ground vehicles.

U.S. AIR FORCE PHOTO BY STAFF SGT. CHRISTOPHER HUBENTHAL

ESSENTIAL RESEARCH AREA:

HUMAN AGENT TEAMING

By Scott R. Gourley

One of ARL's Essential Research Areas (ERA) designed to address the future needs of U.S. warfighters involves Human Agent Teaming (HAT).

"Today's Soldier teams provide the capability to complete the mission – any mission," offered Kaleb McDowell, Chief Scientist in the U.S. Army Research Laboratory's Human Research and Engineering Directorate (ARL-HRED) and Lead of the HAT ERA. He noted that the ARL focus within the HAT ERA seeks to create teams of humans and intelligent agents that have the capability to perform as well as today's Soldier teams but also feature additional capabilities, such as greater team resilience with robust, adaptive performance; fast, dynamic team reconfiguration to match capabilities to continually evolving mission requirements; faster, more informed decision making; and, perhaps most importantly, reduced risk to Soldiers.

Much of the HAT vision is reflected in the future complex urban environment envisioned by the U.S. Army's Training and Doctrine Command (TRADOC) as the multi-domain battlespace comprising land, air, sea, space, and cyberspace.

In the not too distant future, TRADOC analysts are estimating that more than 70 percent of the world's population will be living in some sort of urban areas. Those urban areas – so-called megacities – will present the U.S. Army with an extremely challenging multi-dimensional operational environment where opponents will have a plethora of structural, cyber, and electromagnetic fighting positions, while potentially surrounded by a civilian population which, itself, may contain enemy, friendly, and "gray" actors with respect to U.S. interests. The net result will be a massive urban space presenting a range of significant challenges to the Army's multi-domain battle operations.

Anticipating that some of those scale and complexity challenges could potentially overwhelm human teams, with one solution to this tactical challenge featuring the introduction of non-human intelligent agents, including manned, unmanned, and optionally manned airborne, ground, sensor, cyber, and other advanced platforms.

The United States won't be alone in introducing these non-human agents. Other countries are already introducing early generations of unmanned air vehicles (UAVs) and other robotic vehicle platforms into their tactical combat planning. Moreover, adversaries may be expected to employ more lenient rules of engagement (ROE) than expected to remain part of the United States military doctrine. The potential for non-human lethality, whether intentional or unintentional, is just one way that these agents could also pose a potentially game-changing risk to United States Soldiers on tomorrow's battlefields.

U.S. Army 1st Lt. Nicholas Kocher, deployed in support of Combined Joint Task Force-Operation Inherent Resolve and assigned to 2nd Brigade Combat Team, 82nd Airborne Division, in Mosul, Iraq, May 25, 2017. Urban areas present an extremely challenging multi-dimensional operational environment.

U.S. ARMY PHOTO BY CPL. RACHEL DIEHM

"Humans are not fast enough and could be overwhelmed in that environment," asserted Jason Metcalfe, a Research Scientist at ARL-HRED and Deputy on the HAT ERA. "I personally would not want to put a Soldier on an open battlefield that's dominated by autonomy based on today's capability because that individual is probably going to end up at severe risk."

Metcalfe said that the optimum solution is not a pure autonomous battlefield but rather a mix of human Soldiers and non-human agents.

He offered the example of two identical side-by-side buildings, one being high value and the other not. Even though the structures may look exactly the same, there are cues that a human can pick up on and immediately comprehend which one is more important.

"You need human reasoning and adaptation capabilities that autonomous agents are just simply not yet ready to handle," he said. "But, at the same time, humans can't handle nearly the amount of data that artificial intelligence and computers can. We don't operate at those speeds. We are nowhere near as precise at targeting things and driving. Consequently, there is a lot of capability to be gained by having a variety of different automated assets, these intelligent agents, working together with humans."

One way that ARL is helping to maximize the effectiveness of Soldiers and their non-human team members while minimizing the future danger to the human element is to focus on the interactions between that Soldier and his or her own autonomous battlefield companions.

And that is an overarching vision for ARL's HAT ERA.

According to Metcalfe, the HAT effort gained significant traction around the middle of 2016, when several members of ARL's Senior Technical Council wanted to start identifying and addressing specific technical gaps and assigning related aspirational goals.

With at least a dozen critical gaps identified and prioritized to date, current HAT ERA efforts are being directed toward five broad research goals: Tailoring Information to Individual Soldiers and Intelligent Agents; Human-Agent Collaborative Decision Making; Enabling Effective Team Responses to Dynamic Events; Enabling Dynamic Team Composition Across Missions; and Human-Intelligent Agent Teaming Analysis.

These research goals are heavily influenced by doctrine and can be enabled through research in areas such as training; individual resilience, readiness, and augmentation; and intelligent agent development, among others.

The first of HAT's broad research goals, Tailoring Information to Individual Soldiers and Intelligent Agents, involves things like estimating blue/red/gray/unknown human and agent behavior and intent, thereby enabling blue forces to build situational awareness across multiple human-agent teams and act earlier. The research also encompasses novel human-agent interfaces and information exchange modalities to allow Soldiers and agents to communicate faster and more effectively. One additional element is context-based information sharing that efficiently provides the information each Soldier/agent needs and aims to unburden the Soldier to enable better decision making at high operational tempos under high risk.

"Human-system performance is not just limited by computing power and bandwidth, but also by the ability of machines to understand us," McDowell said.

Consequently, one of the identified critical gaps in this area is a need for capability to estimate and predict human variability, behavior, and intent across dynamic contexts (tasks, people, and environment) given multiple, disparate sources.

Additionally, since current system design approaches limit functionality and force humans to adapt to systems because they do not systematically contend with human variability, another gap points to a need for methods to effectively share concepts, intentions, and situations across heterogeneous human-agent teams strongly inhibited by platform differences and technological divides.

Said another way, the ideal picture would be teams of both humans and non-human agents performing with levels of capability and adaptability that neither group could achieve alone.

Homogeneous human teams reflect a certain amount of unstated recognition and understanding between team members. For example, members of human teams that have operated together for any length of time will quickly recognize when one team member is "on their A-game" or when they might be struggling due to minor injury or some other reason. In those instances they might assume some portion of a load or automatically prepare to provide backup to a particularly challenging task.

But how can that type of unstated understanding be conveyed to non-human agents so that they can potentially "pick up the slack" where necessary?

Metcalfe pointed to a significant amount of research already conducted in linked, partially overlapping domains such as human-robot interaction, human-computer interaction, man-machine interaction, man-machine teaming, and others broadly considered in human-system integration.

"There are certainly people working on this," he said. "But what ARL is trying to do is focus on this problem from an Army perspective, because research happening outside of the DOD is not likely to address either the complex tasks, teaming needs, and/or environmental challenges that the Army will need to overcome. We have the resources and the relationships to connect with people who are also doing this kind of research, to really throw a lot of the government and Department of Defense weight at the critical piece that many continue to struggle to solve in a general way. The fact is, if we can't make things work together in cohesive, mutually adaptive teams, we are not going to be able to do what we need to do in the future multi-domain battlespace. Our forces will require advanced human-agent teams to create and subsequently take advantage of very short windows of time within which we establish decisive overmatch sufficient to conquer adversaries and stabilize areas of strategic advantage."

Specific research projects are directed toward estimating and predicting human variability, agent trust and transparency, and behavior and intent prediction for all teammates, human and non-human, as well as sharing concepts, intentions, and awareness across heterogeneous HAT teams. The closed-loop nature of this research emphasizes the importance for members of high-performing teams to have shared world models about tasks, teammates, and goals.

A second broad research goal for the HAT ERA focuses on Human-Agent Collaborative Decision Making.

Collaborative human-agent decision methods and models emerging from this research will provide capability to increase the speed and reliability of decisions for overwhelming operational tempo, with joint human-agent decision-making and reasoning transforming how future Soldiers collaborate with intelligent agents and the roles the Soldiers perform.

The research recognizes a current identified gap that humans are able to adapt to the complexities and dynamics of real-world operational environments to a degree unmatched by current forms of autonomy, but they simply can neither process the amount of information potentially available nor understand the reasoning underlying complex, intelligent agents.

Metcalfe characterized the efforts as getting systems of agents working together to make operational decisions at operational tempos – if not in some cases faster.

"This becomes a problem of distributed intelligence," he explained. "Human teams can make decisions, even when each person might have seen or received different pieces of information. Then collaboratively, through command relationships, consensus, or majority vote, they come to a singular decision."

By contrast, the current state of the art in artificial intelligence for distributed reasoning and decision-making points toward general consensus-based methods, where different algorithms slowly arrive at a singular decision.

According to Metcalfe, such current types of processes may even be (and often are) slower than human decision-making and will therefore not support broad human-agent teams on complex multi-domain battlefields.

One representative example of several current ARL efforts being focused on the collaborative HAT decision-making challenge is exploring novel forms of joint human-intelligent agent decision-making by focusing on innovative approaches in three separate concept areas: cases where intelligent agents can solve much of a problem with or without some human input; cases where humans can solve problems on their own, but intelligent agents may offer contributions; and cases where neither humans nor intelligent agents can solve a problem independently.

U.S. Army Spc. Logan Fishburn, 2nd Battalion, 27th Infantry Regiment, 3rd Brigade Combat Team, 25th Infantry Division, tests a PD-100 unmanned aerial vehicle during the Pacific Manned-Unmanned Initiative July 22, 2016, at Marine Corps Training Area Bellows, Hawaii. One way that the Army Research Laboratory is helping to maximize the effectiveness of Soldiers and their non-human team members is to focus on the interactions between them.

U.S. AIR FORCE PHOTO BY STAFF SGT. CHRISTOPHER HUBENTHAL

Other related research falls under the broad category of Augmenting Human Capabilities for Collaboration with Rapid Agent Advances, and includes projects focused on Rapid Capability Enhancement through Integrated Augmentation and Training, and Urban Interactive Immersive Training Capability. Other supporting efforts are looking at adaptive training, core modeling and simulation enablers for megacity applications, and augmented- or mixed-reality training.

In coordination with and leveraging off of these efforts, a third broad research goal for HAT focuses on Enabling Effective Team Responses to Dynamic Events. Aspects of the research range from distributed intelligence and intent recognition to enable unified team reaction and increased resilience with disrupted local communications to an effective HAT design that reduces both physical and mental burdens to facilitate Soldier focus on the mission.

The applicability of this research is particularly evident in the case of an urban environment where the presence of civilian populations can translate to rapidly changing rules of engagement.

Metcalfe offered the example of a student protest that suddenly evolved into something far more sinister and potentially dangerous with the arrival of malicious actors from outside, or who perhaps were embedded within the group from the outset.

"How is the team that's six blocks down in this megacity able to know that suddenly the game has changed?" he asked. "We're in a very different circumstance, especially if our communications are getting jammed or our sensor feeds are not reliable. So the goal of this particular piece of research is to enable effective team responses to dynamic events like this."

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The shadows of M1A1 Abrams crew members are cast on the tank at the Army National Training Center at Fort Irwin, California. ARL is carrying out basic and applied research to support Army operations in a future battlespace likely to be less about humans crewing machines than humans and intelligent agents working together as a team.

PHOTO BY MASTER SGT. ADRIAN CADIZ

Related HAT research projects include both distributed and collaborative intelligent systems and technology and exploring the internet of battlefield things for persistent intelligence, surveillance, and reconnaissance (ISR).

In the case of the former, the cooperative effort will involve enabling research and technology to extend the reach, situational awareness, and operational effectiveness of HAT against dynamic threats in complex and contested environments and provide technical and operational superiority through fast, intelligent, resilient, and collaborative behaviors.

The latter effort will shift emphasis somewhat toward research and engineering approaches for understanding dynamic composition of heterogeneous sensors, people, cyber networks, and processing algorithms; adaptive, environment-aware, mission-driven distributed asset management and allocation; and autonomous repurposing and re-tasking of assets.

Metcalfe characterized these upcoming efforts as "really exciting groundbreaking science."

Other supporting activities include multiple efforts for local human coordination with and control (mounted and dismounted) of both unmanned and manned (or optionally manned) systems.

In addition to decision-making in dynamic environments, the HAT ERA is also directing research toward a capability that results in Enabling Dynamic Team Composition Across Missions.

Aspects of this research goal aim to address intelligent assistants that help Soldiers, individually and in teams, to quickly adjust to new roles and responsibilities in HAT, to help a new Soldier quickly learn the intricacies of an established HAT to build team cohesion, and to identify knowledge and skills gaps across HAT members to improve team performance.

Emphasizing the aspect of "team composition," Metcalfe offered the example of a heterogeneous human-agent team that has been sent to address a dynamic event.

"But what if something changes about your team? What if you lose an asset, like a UAV that was providing you with situational awareness across multiple missions? You've been training with that asset and these people for months. And suddenly it has to change out. If you get a new commander or a new machine gunner, the team itself has to recalibrate in terms of how they make decisions or convey information. Now they will need to understand the needs of a new agent (human or non-human) relative to the team," he said.

The HAT ERA efforts are supported by the fifth primary research area: Human-Intelligent Agent Teaming Analysis. The research explores tools to verify and validate HAT performance across Soldiers, agents, and conditions prior to fielding as well as tools to provide insights and enhance technology development from early prototypes through acquisition and fielding

This research takes a different approach from the other areas in that it is not directly about ongoing analyses that support the mission as it unfolds, but instead focuses on establishing metrics that allow accurate assessment of the performance outcomes of HAT teaming technologies before they reach the field so that expectations about Soldier-agent teaming can be validated, verified, and even improved on successive cycles.

Metcalfe acknowledged that, at first blush, this might sound like research that has already been performed. In fact, that analysis to date has largely focused on either the Soldier or agent side of the human-agent team, but not both together as a functional unit. ARL is breaking new ground in a team analysis approach that enables better insights into critical aspects of HAT operational effectiveness.

Metcalfe concluded with the acknowledgement that, although early exploration of human-robot and human-computer interactions have been undertaken for many years, it has not panned out as first envisioned in military spaces. Indeed, though robotic assets have seen more use in Army and other military operations, they have not exactly been the force multiplier that they were first anticipated to be. This is especially because most advanced operational technologies involving robots still require at least one, if not several, Soldiers to control them – as advanced tools – rather than work with them as teammates.

"It's not broadly fielded at this point," he said. "And we would argue that important reasons why this is the case are captured by the gaps identified in the five goal areas and related research topics of focus within the HAT ERA." In most situations agents have not yet been accepted as teammates, but are simply still used as tools when convenient. If the intention is for autonomy to play a larger role in Army objectives, transitioning from tools to teammates is an essential requirement.

GDJ IMAGE VIA WKIMEDIA COMMONS

ESSENTIAL RESEARCH AREA:

ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING

By Craig Collins

Future operations will require warfighters to prevail in a complex world such as large-scale, cluttered, contested urban environments. To address future challenges, the Army S&T portfolio is focused toward acceleration of priority technologies that include the Chief of Staff of the Army (CSA) Priorities and also Capability Enablers for 2026 and beyond [1]. Three of the key Capability Enablers being addressed by the U.S. Army Research Laboratory (ARL) S&T campaigns in Information Sciences and Computational Sciences are:

- Decide Faster – high operational tempo
- Manned-Unmanned Teaming – enhanced mobility
- Asymmetric Vision – improved situational understanding

To further focus the S&T essential to ARL's highest priority work, the Essential Research Areas (ERAs) were identified [2]. The ERAs have been developed with the understanding that future warfare will be fought across multiple domains (i.e., Land, Air, Space, Cyberspace, and Maritime) and among three realms: the physical, the domain of activities defined in space and time by the laws of physics; the informational or virtual, the domain of activities defined by thought and perception; and cultural (or human), the domain of activities defined by the interaction of people and societies.

In a future battlespace, Soldiers trying to track and respond to threats could rapidly become overloaded – which is why the Army is placing such a strong research emphasis on the development of intelligent systems that can help share this burden and keep Soldiers mission-focused. The main research area addressing intelligent systems operating in complex environments is Artificial Intelligence and Machine Learning (AI & ML) along with research from Human-Agent Teaming (HAT) and Cyber and Electromagnetic Technologies for Complex Environments (CETCE) ERAs.

While the "smart" technology used by warfighters today is far more intelligent and easier to use than ever before, it's not smart enough for this future battlespace. Today's unmanned systems are extensions of individuals or teams of Soldiers, following directions to achieve increasingly complex tasks. But they're not intelligent agents – machines capable of perceiving their environments and acting to maximize their chances of achieving assigned objectives.

AI exists in several forms today. Computers can recognize and interpret optical characters, human speech, and faces. They can beat people at chess. They can interpret complex data to filter out spam or recommend the best route home from work. These are important milestones, but they're milestones in achieving narrowly defined tasks. There's still much they can't do, activities and decision chains involving multiple simultaneous inputs. Despite the media buzz, for example, there's no such thing – yet – as a self-driving vehicle.

ARL researchers must overcome several obstacles to develop true working teammates with AI, and they must work from a different set of assumptions than their counterparts in industry and academia, who generally focus on "narrow" tasks such as object recognition. Compared to such commercial applications, military domains are likely to change more rapidly; be fraught with noisy, incomplete and potentially erroneous data; and subject to an adversary's efforts at disruption and deception. In addition, access to data for training military-specific AI is very difficult to obtain. The ARL's work in developing a military-specific AI will focus particularly on approaches and applications relevant to the needs of the Army.


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ARMY RESEARCH LABORATORY IMAGE

■ To support operations on future, complex battlefields, U.S. Army Research Laboratory (ARL) S&T campaigns are addressing three key Capability Enablers in Information Sciences and Computational Sciences.

Learning in Complex, Contested Data Environments

One of the most important questions being explored by ARL investigators is an issue to which private industry, understandably, hasn't devoted many resources: How do you write ML algorithms and train an artificial intelligence to work in an unfamiliar environment, feeding small samples of new, "dirty" and highly heterogeneous data into your AI, while an adversary is trying to deceive?

According to Tien Pham, PhD, ARL's Senior Campaign Scientist (SCS) for Information Sciences, the challenge of making AI work in the real world is that it doesn't offer the same controlled, thorough, reiterative opportunities for machine learning as the laboratory. "Machine learning requires lots of data for training," he said. "And a lot of it has to be very well-curated data, data that's labeled, that doesn't have a lot of noise, and so forth. And none of that exists for us in the military domain." The battlefield is, to put it mildly, an uncontrolled environment. Things happen fast. Information can be incomplete, overwhelmingly complex, or contradictory. Adversaries, rather than trying to teach your robotic teammates, are working to confound them.

For machines that operate in both the physical and cyber realms, the possibilities for deception are head-spinning. Ananthram Swami, PhD, the Army Senior Research Scientist (ST) for Network Science, explained that the complexity of deep learning algorithms gives adversaries multiple opportunities to manipulate an AI's perceptions.

"The problem is that we don't, in many cases, have a good understanding of how some of these learning algorithms work," Swami said, "and because we don't have a very good understanding of how they work, we don't have a good understanding of how they can be deceived – and therefore how they can be made robust as well."

Since 2013, the ARL has been working within the Cyber Security Collaborative Research Alliance (CRA) to address what Swami describes as the key question related to adversarial ML: "How do I make my learning algorithms robust against manipulation?" The CRA, led by Pennsylvania State University, includes partners from industry, academia, and the U.S. Army Communications-Electronics Research, Development and Engineering Center (CERDEC).

This would be particularly problematic with a system designed for autonomy – one of the stretch goals for the AI & ML ERA group. On the future battlefield, the ARL believes deployed Soldiers and tactical units will be assisted by numerous intelligent robot teammates, each with a degree of autonomy. These intelligent systems of the future must operate in challenging, militarily relevant environments. They must act in concert with Soldiers, commanders and other intelligent systems. And they must make decisions within and beyond the human operational tempo.

U.S. ARMY PHOTO BY JHI SCOTT

Stuart Young, PhD, of ARL's Computational & Information Sciences Directorate, presents the Autonomous Systems Manned/Unmanned Teaming technology to the commanding general of the U.S. Army Research, Development and Engineering Command, Maj. Gen. Cedric T. Wins, during DOD's Lab Day at the Pentagon. While robots have become more common in the battlespace, the vital next step in manned/unmanned teaming is the very challenging goal of a measure of autonomy for robotic systems.

ARL is exploring the underpinning science – of which AI and ML are the foundation – that will transform these robots into teammates. Since 2009, the ARL has participated in the Robotics Collaborative Technology Alliance (CTA), with a major emphasis on the techniques (tactical reasoning, proactive human interaction, etc.) necessary for robots to establish and assert a level of autonomy that will unburden their Soldier teammates. Stuart Young, PhD, Chief of the Information Sciences Division, who manages the Robotics CTA, explained that in these autonomous roles, intelligent robots must be able to reason about the world in ways similar to that of Soldiers, make mission-consistent decisions, and adapt to unexpected situations that either arise from the environment or are imposed by adversaries.

To meet these challenges, ARL researchers are developing machine learning algorithms that build on the successes of industry and academia – with a focus on building robots that can perform in novel environments with less pre-loaded data and ML.

Resource-Constrained AI Processing at the Point of Need

AI that can provide a tactical unit with situational awareness, analytical power, and platform autonomy will have to operate over a dispersed area, most likely with limited communications and computing infrastructure. It will have to run on hardware with extremely low size, weight, power and time (SWAPT) available.

One of the critical issues for the Army is the amount of computing power needed to run the processing-heavy algorithms necessary for machine learning (ML) – the process by which a computer learns from data without being explicitly programmed where to look. When an AI service like Apple's Siri answers your question, it's not using the processor in your phone; it's sending the query out into

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Imagery depicting neurons in the human brain. While the brain requires the equivalent of between 5 and 20 watts of power, simulating the performance of the brain's 100 billion neurons in traditional computing architectures would require about 10 megawatts of power, or the output of a small hydroelectric plant.

the cloud, where a huge network of servers and processors handles it. These tools have enough power to execute a specific type of ML known as "deep learning," which recognizes data patterns and offers recommendations and solutions (i.e., facial recognition or route navigation).

The traditional hardware necessary to perform this computing requires about 200 to 300 watts of power to run ML algorithms. According to Manuel Vindiola, PhD, a research psychologist with the ARL, this is one of the most significant challenges facing Army investigators as they work to bring AI to the field: "If you're in a low-power situation, and you just can't plug in your phone, in a place where you don't have access to the cloud and the internet," he said, "how do you do this kind of computing for days, weeks, months, and even years?"

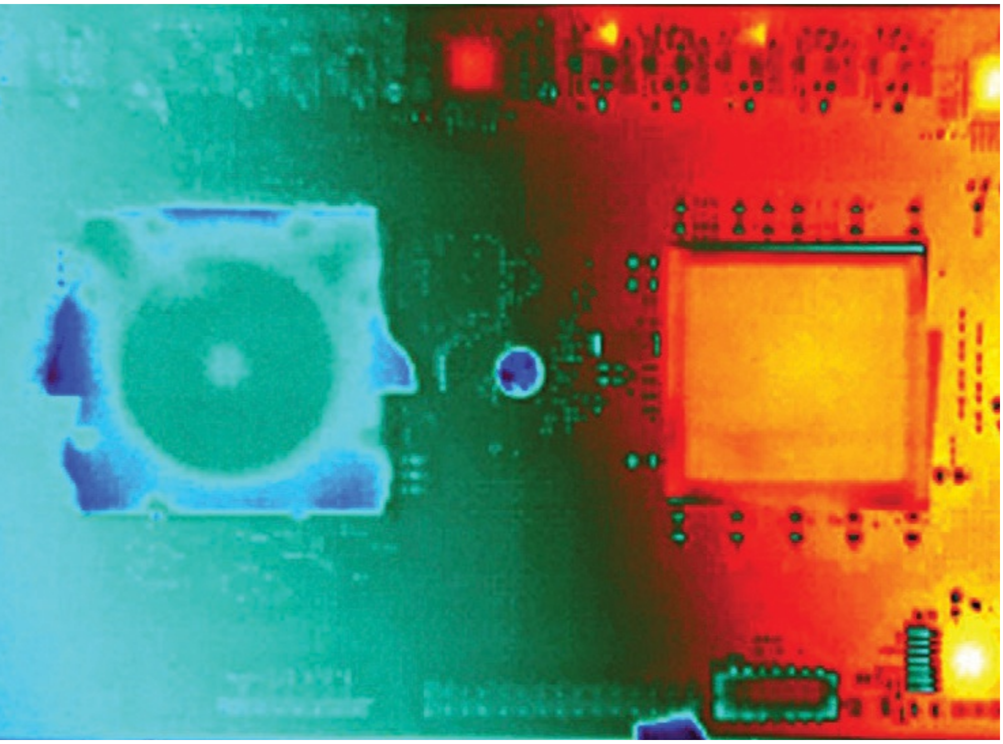
The brain provides a far more efficient model for information processing – it contains 100 billion neurons but requires the equivalent of between 5 and 20 watts of power, maybe enough to power a bedroom nightlight. Neurons fire electrochemical signals, or "spikes," in parallel, at different intervals, to communicate across neural synapses. These "spike trains" are analogous to digital sequences of data, generated in response to sensory stimuli – sights, sounds, smells, tastes, or physical contact – or abstractions such as memories, math problems, or emotions. In recent years, industry has brought "neuromorphic" architectures to the market that mimic the way the brain processes information. IBM's TrueNorth chip, unveiled in 2014, processes data using a network of more than a million "neurons," connected by 256 million "synapses" that can perform 46 billion synaptic operations per second. It's the closest the computing industry has come to replicating a neural network, and a single TrueNorth chip consumes about 70 milliwatts – 0.07 of a watt, about 1/10,000th the power density of traditional microprocessors.

Programming the first generation of autonomous teammates with this kind of hardware will require an accompanying sea change among computer scientists. The deep learning algorithms that allow smartphones to recognize faces and supply navigational recommendations were written using programming languages and tools built around the model of logical operations and their linear input/output cycles. "The neuromorphic systems we have right now aren't capable of learning on their own yet," said Vindiola. "We now need a way to learn in spikes. And we don't know how to do that."

Another important focus for the ARL's AI and ML experts is to look at conventional problems, solvable with traditional architectures, and figure out a way to reprogram those processes onto a neuromorphic architecture.

In the spring of 2017, ARL researchers and their partners at DCS Corp demonstrated how they had used datasets of human brainwaves, fed into a neural network, to improve the ability of the network to identify a target in a dynamic environment. The researchers taught the AI to recognize when human snipers had made targeting decisions.

Such recognition is an important first step to establishing situational awareness in a dynamic environment. According to Brian



The IBM NS1e mobile development system houses the low-power IBM TrueNorth neuromorphic chip. While ARL is not working on creating neuromorphic systems or hardware, a small team of ARL computer scientists is working to develop programming that will work with neuromorphic chips.

Henz, PhD, ARL's Senior Campaign Scientist (SCS) for Computational Sciences, the ability to do learning on a neural network opens up new possibilities for Soldiers: "We're working to put the models they've developed on, say, something a Soldier could wear, because it's very low-power and runs very quickly." The most obvious example of how such a system might be used, he said, would be for the purpose of image tracking or image recognition in live video feeds.

UAVs, in particular, could use neural networks to analyze video feeds and remain in contact with Soldiers, recognizing landmarks or targets without the hefty computers now needed to process imagery. Rather than sending raw video of a crowd, for example, the UAV could send the information that one of the people in the crowd is behaving suspiciously – running, or carrying a weapon.

The exponential increases in computing power, coupled with corresponding reductions in energy consumption, may make neuromorphic architectures appropriate for other tasks as well, Henz said, and a team of ARL researchers is investigating the programming that will be necessary to adapt these architectures to the Army's needs. "We're also doing research to use these not only for running AI machine learning algorithms, but also for more traditional things requiring complex programs, like physics-based calculations or analyses of big data sets." ARL materials researchers, for example, work to develop predictive models for how certain materials would behave, down to the level of single atoms.

Generalizable and Predictable AI

In order to be useful in the military domain, AI and ML algorithms must become more robust and more generalizable than they are today, said Pham. "AI and ML have a lot of promise for very specific and narrow problems, with well defined objectives and lots of data to train." Self-driving cars, while a very challenging problem, he said, is still considered to be a well-defined narrow AI problem that relies on substantial quantities of driving data, including traffic patterns and street signs and weather.

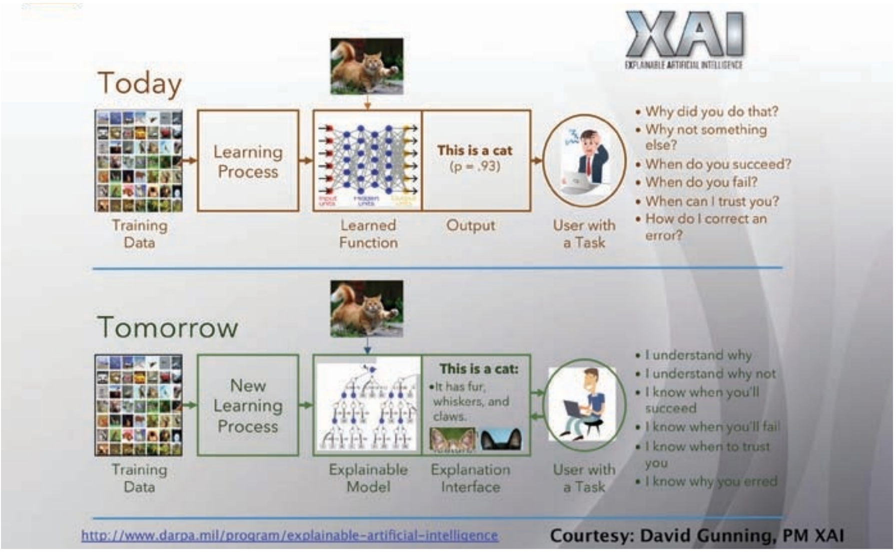
Even within narrowly defined domains, adversaries can – and do – introduce variability. "Imagine you've spent a lot of resources training an AI algorithm to solve a particular kind of IED detection problem with a particular material and shape in the field," said Pham, "and as soon as you developed a viable AI solution for that IED problem, the enemy will adapt and change their tactics, techniques, procedures (TTP). They will use different material and containers and render your previous AI solution useless. We need AI that is more generalizable – that can solve an array of different problems, and adapt to change."

In order to program this kind of learning, the Army needs an AI more capable than what Pham calls a "black box": an application that receives data in one end and spits out a solution at the other. Users will need to understand the AI's thinking about why the solution is the correct one. To develop a system that can share its thinking in this way, the AI & ML researchers will leverage the work of a recent initiative, the Explainable AI (XAI) program, launched by the Defense Advanced Research Projects Agency (DARPA).

If you show a picture or video of a cat to an AI system today it can tell you, with about 99 percent accuracy, "That's a cat." But it can't tell you why it thinks that: Was it the ears? The body shape? The way it walks or moves its tail? Explainable AI will generate not just a conclusion; it will offer users an explainable model, and an interface that will enable them to probe and reveal the system's reasoning.

"Imagine you're an intelligence analyst," Pham said, "and you want to know whether a guy is suspicious or not. You need more than, 'This guy is suspicious.' You really have to understand how it works to be able to interpret and explain the result to the user." Better explainability, Pham said, will loop back directly and feed programmers' ability to make AI more robust and potentially more generalizable. "This is a question that's at the heart of understanding AI and how it works internally," he said.

The ARL's initial focus for these military-specific aspects of AI and ML, Pham said, will likely be the development of a system



ARMY RESEARCH LABORATORY IMAGE

In order to develop an artificial intelligence system that can share its thinking about why a solution is the correct one, ARL's AI/ML group is leveraging the Explainable AI (XAI) program launched by DARPA. While an AI system today can identify a cat, it cannot yet explain why it has reached that conclusion.

that will provide the "Fight's Eye" for a tactical team of human-robot agents. The commander of a small team, operating in a highly cluttered, contested environment with active denial measures imposed by an adversary, could make use of an AI-enabled system – perhaps with the aid of autonomous unmanned teammates in the air and on the ground – that provides real-time situational understanding, and perhaps AI-enabled reasoning to supply a sensible course of action.

A Community of AI Research

The Army and other branches of the U.S. armed forces rarely work alone. Increasingly prevalent and increasingly complex coalition operations multiply the number of data sources, learning algorithms and learning models that feed into a network, as well as the number of protocols for data sharing – what types of data, and how much, can be shared given the constraints of existing communications. "So what this means is that although coalition partners share the same common purpose," said Swami, "each is processing different data items, with different training and learning algorithms. We somehow need these disparate learners to improve their learning capabilities together."

One of the ARL's most recently formed research partnerships, established in September of 2016, is the Distributed Analytics and Information Science (DAIS) International Technology Alliance (ITA), aimed at addressing this very issue. In collaboration with the United Kingdom's Ministry of Defence, ARL investigators are working to develop the research base for distributed analytic systems that are secure, dynamic and self-aware – able to derive a shared, trustworthy situational understanding in coalition operations.

To appreciate the complexity of the obstacles that lie ahead for solutions in Artificial Intelligence and Machine Learning is to understand why it's one of the ARL's foundational research areas, a gateway technology that will enable successes in several of its other ERAs. ARL scientists and engineers will be working within several collaborative research initiatives aimed at closing existing technology gaps: The Distributed and Collaborative Intelligent Systems and Technology (DCIST) CRA, established in September 2017, will focus on AI's significance to the development of distributed intelligence, heterogeneous group control, and adaptive and resilient behaviors. The Internet of Battlefield Things (IoBT) CRA, also established in September 2017, will explore how to imbue these intelligent networks of distributed and potentially widely dispersed IoT-like assets with autonomy, cyber- and physical security, adaptability, and the ability to process and analyze heterogeneous and variable data from hundreds to thousands of disparate data sources.

While these efforts are ramping up, a broad consensus is emerging within the Department of Defense that the complexity of the military operating environment, the lack of a robust ML and generalizable AI solutions, and the commercial and academic sectors' limited familiarity with – and access to – the needs of the military domain, will likely make it necessary to establish an AI/ML research institute hub to promote collaborative research and education in AI/ML and advance the development of robust ML algorithms and AI capabilities and that can operate within the resource constraints of the military domain.

Pham and Henz, who are the AI&ML ERA's co-coordinators at ARL, believe a DOD-wide research center for AI/ML would help to build both the data sets and the expertise needed to meet the challenges ahead. "The reason Google and Facebook are doing so well with AI," said Pham, "is that they have huge amounts of data. If we want to apply machine learning to our military problems, we have to make data more accessible – but the issue there is that the military data for the most part is quite sensitive."

Pham hopes the AI/ML research institute construct will offer both competitive and collaborative opportunities. Breaking down barriers between the users of Army technology and the people who hope to transform those technologies into intelligent systems is an imperative step toward realizing the technology goals. The AI/ML institute's initial focus will likely be research and development on generalized AI and robust ML in both autonomy (robotic systems and software agents acting and interacting in the physical world) and analytics (computer systems and software acting and interacting in the virtual/cyber world).

[1.] Army Science and Technology presentation by Dr. Thomas Russell, April 2017 (Powerpoint)

[2.] U.S. Army Research Lab Essential Research Areas Summary; U.S. Army Research Laboratory, 2017

ESSENTIAL RESEARCH AREA:

CYBER AND ELECTROMAGNETIC TECHNOLOGIES FOR COMPLEX ENVIRONMENTS

By Scott R. Gourley

Historically, Electronic Warfare (EW) and Cyber activities have been separated in operations, research, and system development. Clear evidence of this separation is found in the traditional use of separate military occupation specialties to identify service members trained and operating in these two fields.

However, it is now widely recognized that future challenges will require the broad integration of EW and Cyber technologies and activities, as well as a possible shift for EW to a more surgically offensive posture against more advanced adversarial systems.

One result of this has been the establishment of the Army Research Laboratory (ARL) Essential Research Area (ERA) titled "Cyber and Electromagnetic Technologies for Complex Environments" (CETCE), which is focused on providing both basic and applied research to enable tactical Cyber and Electro Magnetic Activity (CEMA) dominance through non-kinetic fires, protection against all CEMA threats in a tactical environment, sensing the electromagnetic and cyberspace environment, and providing mobility within the battlefield and cyberspace.

According to Thomas Stadterman, PhD, ARL's Senior Campaign Scientist, Analysis and Assessment Campaign and coordinator for the CETCE ERA, the underlying process began in May 2016, when a series of meetings generated "scientific questions that ARL should answer, with near term demonstration."

"From those questions and demonstrations, we identified centralized themes and ARL 'must do' activities, which formed the basis for the Essential Research Areas," he said.

"None of the ERAs are totally new," he quickly added. "There has been research underway in each of these different areas. But now we are focusing the research, identifying research gaps, and developing research plans to fill these gaps. The ERAs are real, executable programs that ensure ARL's research projects are connected, cumulative, and converged to realize an outcome.

"For example, our CETCE Essential Research Area is associated with tactical level cyber and electromagnetic activity," he continued. "Our objective is to provide the foundational research, the basic and applied research, to enable the Army to have dominance in this tactical area that we refer to as Cyber and Electro Magnetic Activity, or CEMA. It is directed towards supporting troops conducting tactical maneuvers within the battlespace by providing them with protection against cyber or electronic warfare threats, enabling potential non-kinetic effects on the enemy and looking at sensing and processing issues surrounding situational awareness related to both electromagnetic and cyber environments. All of this will help to enable troops [to] successfully complete their mission in a complex battlefield."

Providing basic and applied research to enable tactical CEMA dominance can be viewed in four major categories: Shoot; Defend; Sense; and Move.

Shoot, for example, entails providing some level of non-kinetic fires to eliminate or degrade threat capabilities. Defend involves protecting against all CEMA threats in a tactical environment. Sense is to fully understand the electromagnetic and cyberspace environment. Move relates to the ability to maneuver within the battlefield and cyberspace, as highlighted by Stadterman.

Noting that researchers are envisioning capabilities resulting from the basic and applied research based on "a set of distributed heterogeneous platforms," Stadterman explained, "Basically that means it could be different kinds of platforms, like unmanned aerial vehicles, unmanned ground vehicles, Soldier-worn sensors or radios, and manned ground vehicles."

"So it's going to be a combination of all of these platforms providing these capabilities," he said.

Emphasizing the historic uniqueness of doing cyber and EW together, Patrick Horton, Lead for the CETCE ERA program management support, pointed to the synergies that could be obtained through a new paradigm that views those two areas together.

"Everything is a computer today," he observed. "That's true whether it's a civilian refrigerator or cell phone or an Army radio or tank. They are all, essentially, rolling or operating computers. That means that there is cyber in everything – whether you like it or not. And a lot of those devices use EW-susceptible technologies, like Wi-Fi or Bluetooth. There is a great deal of wireless technology in almost everything, so you really do have to address cyber and EW issues together.

As with most of the other ARL ERAs, the identification of existing technical research gaps has enabled ARL scientists to focus the supporting research in seven broad areas: EM Enabled Cyberspace Operations; Understanding CEMA Effects; Understanding Human Behaviors Related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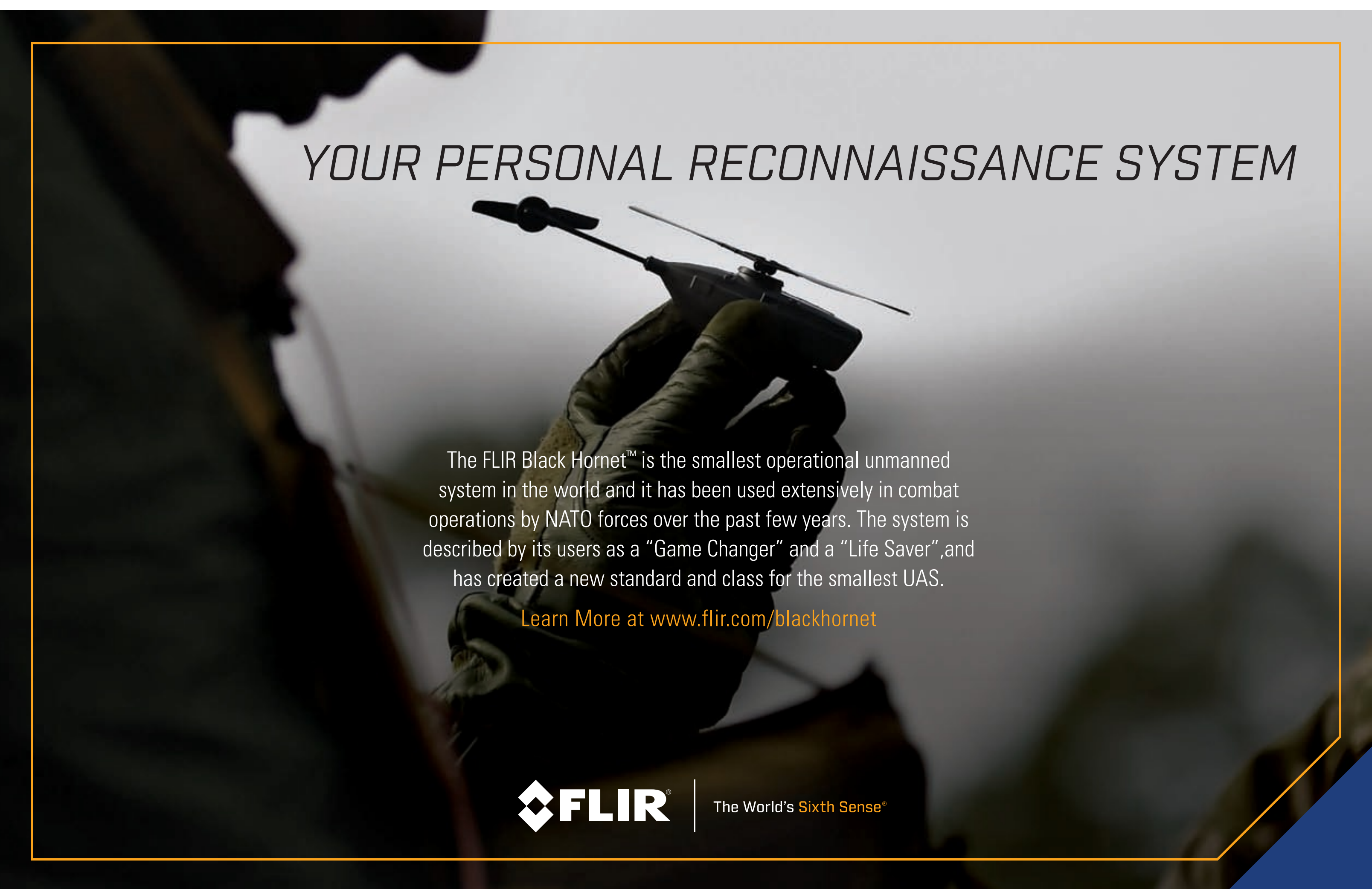
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to CEMA; Cognitive Sensing and Processing of Cyber and EM Information; Camouflage and Decoy of CEMA; Complementary PNT [Position, Navigation, and Timing] approaches; and Alternate Dynamic Communication Approaches.

In turn, those research areas are organized and categorized within one of three CEMA "clusters." The first three noted above are grouped in a CEMA Effects Cluster. The next two are in a CEMA Spectrum Understanding and Control Cluster. And the last two are in a cluster identified as Distributed PNT and Communications for Collaborative CEMA.

Starting through the research areas, Stadterman explained that EM Enabled Cyberspace Operations requires developing protection against EM-enabled CEMA threats, EM characterization of the "internet of battlefield things," distributed-cooperative EM/cyber effects, detection and characterization of vulnerabilities in a CEMA operation that blends EW and cyber in order to harden blue systems and assess EM-enabled cyberspace technologies and systems.

Examples of potential products that could emerge from this research range from counter unmanned aerial systems (UAS) to new concepts for CEMA camouflage.

Research payoffs would be significant, and would include new Army capabilities like disruption of adversary UAS operations, methodologies to analyze threat effects of combined large-scale cyber and EW in heterogeneous systems, efficient and accurate protocol reverse engineering capabilities for complex and cross-domain systems, attacker/defender/operator-based models for decision support in large-scale hybrid environments, low-cost and efficient analysis capabilities for "non-standard" (non-internet protocol) and embedded devices, methodologies and tools to assess combined multi network-layer threats, distributed cooperative electronic attack and deception projected from multiple disparate emitters, and threat agnostic electronic attack without a priori susceptibility characterization of targets.

The purposes underlying the second research area, Understanding CEMA Effects, include understanding CEMA effects across all functional layers, characterizing the interfaces between functional layers, characterizing propagation of CEMA effects across all functional layers, and providing an

Pfc. Nathaniel Ortiz of the 780th Military Intelligence Brigade sets up deployable cyber tools overlooking the mock city of Razish at the National Training Center at Fort Irwin, California, in support of a pre-deployment training rotation for the 2nd Armored Brigade Combat Team, 1st Infantry Division, as part of the Army Cyber Command-led Cyber Electromagnetic Activities Support to Corps and Below initiative. The ARL Essential Research Area Cyber and Electromagnetic Technologies for Complex Environments is focused on providing basic and applied research to enable tactical Cyber and Electro Magnetic Activity (CEMA) dominance for the Army.

PHOTO BY BILL ROCHE

environment to analyze and assess CEMA technologies and their potential effects across all layers.

Again, significant Army payoffs would range from the awareness of CEMA effectiveness in all situations to the ability to characterize potential battle damage and collateral damage.

Understanding Human Behaviors Related to CEMA encompasses the following: addressing critical Soldier-system integration challenges underlying the maturation of forces capable of converged kinetic, cyber, and electromagnetic activities; developing novel methods and tools for optimizing CEMA decision-making and collaboration in operational environments; and fostering new integrated Soldier-system CEMA decide-faster and asymmetric visualization capabilities.

"There will be so much information about the electromagnetic and cyber environment from all of the sensors that there will have to be decision aids for the Soldier," Stadterman said. "Obviously that will tie research between the Artificial Intelligence/Machine Learning and Human-Agent Teaming ERAs and our CETCE ERA."

The two research areas grouped within the CEMA Spectrum Understanding and Control Cluster are Cognitive Sensing and Processing of Cyber and EW Information and Camouflage and Decoy of CEMA. Both research areas meet the general purpose of the cluster, which is to enable electromagnetically inconspicuous Army platforms and dismounts, while maintaining freedom to maneuver, communicate, and sense using cognitive constructs (e.g., situational awareness), complex adaptive networks, and data processing.

Within Cognitive Sensing and Processing of Cyber and EM Information, Stadterman offered one "vision of success" that included predictive analysis into trustworthiness of data, perception, vulnerability detection, avoidance, and projection as well as automated cognitive decision-making processes with modeling and simulation algorithms, software, and devices.

Additionally, he identified a range of success measures in the research of Camouflage and Decoy of CEMA that could include: Low cyber/electromagnetic visibility; "Free" geolocation via distributed decoys

dual-hatting as sensors; Improved understanding of geolocation techniques and vulnerabilities; Force protection against kinetic and non-kinetic effects; "Hide in plain sight"/exploit congested operational environment chaos; and Validation of dynamic honey pot capability for reasonable threat models.

The final two research areas fall under a grouping cluster identified as PNT and Communications. Key terminology here includes Low Probability of Intercept/Low Probability of Detection (LPI/LPD), with those goals applied to communication and datalinks that can be utilized for sharing position and timing information.

Other enabling capabilities in the cluster range from novel tactical optical communications capabilities that could enable communications in severely contested RF environments to communications and localization in highly cluttered environments by exploiting penetration and lack of multipath effects in low-VHF.

In a similar fashion to the other clusters, this one also offers a range of enabling outcomes and products. As two examples, Stadterman pointed to the ability to provide trusted information for the U.S. Army's warfighting challenge of developing enhanced situational awareness as well as the integration of PNT and CEMA for a future potential "navigation war."

Other resulting products could include frameworks for channel modeling and simulation and system and network design, secure, short range, high atmospheric absorption datalinks, asymmetric architectures, hardware (sensors, computation, time transfer, etc.), and algorithms that leverage the heterogeneous nature of the hardware and information employed to realize new approaches to trusted PNT, methodologies for real-time calibration and increased accuracy across multiple system reference frames/coordinate systems and addressing issues in latency, denied, or missing data from distributed and heterogeneous systems and sensors, novel miniature low-VHF passive and active antenna designs, and ultra-fast time transfer techniques including network protocols and free space time transfer.

Asked about outside research and cooperation with other agencies and academia, Stadterman pointed to significant interaction with the U.S. Army's

■ **Spc. Rodolfo Lara, a member of the Expeditionary CEMA (Cyber Electro Magnetic Activities) Team, 781st Military Intelligence Battalion, conducts cyberspace operations while supporting the 2nd Armored Brigade Combat Team, 1st Infantry Division, during their Danger Focus Field Training Exercise at Fort Riley, Kansas. The development of electronic warfare and cyber technologies and tactics has become necessary to support the U.S. Army in the modern battlespace.**

U.S. ARMY PHOTO

Communications Electronics Research Development and Engineering Center (CERDEC) and product managers within the Army's Program Executive Office for Intelligence Electronic Warfare and Sensors (PEO IEW&S).

"We also had a recent meeting where we had some visitors from the Army's Cyber Command," he added. "And we're just getting started. We are working with many other people at various levels at places like the U.S. Army's Training and Doctrine Command (TRADOC) Asymmetric Warfare Group. And we have a meeting planned in the near future with TRADOC's Cyber Center of Excellence."

Looking beyond Army organizations, he continued, "We also had a recent meeting that has resulted in our partnering with the Office of Naval Research and Northeastern University Kostas Research Institute on Expeditionary Cyber, which is terminology they use in conjunction with their work supporting the Marine Corps." This partnership is associated with ARL-Northeast.

"We are not working with the Air Force yet," he added. "But I understand that they are doing some work in understanding cyber effects, so we will be looking to work with them as well."

In terms of possible future directions for the research, Stadterman pointed to some of the planned defensive cyber work being planned for so-called "cyber physical systems," which will enhance protection for electronics and software on both ground and air vehicles.

"The future is also going to require autonomous vehicles that incorporate artificial intelligence and machine learning," he offered. "So that will create a tie-in to other Essential Research Areas."

He noted that future research efforts will also include emphasis on things like position navigation and timing and new types of communications.

"The area of camouflage will also be expanded in the future," he said. "That will include camouflaging us in terms of what signals we are sending out as well as camouflaging any protection aspects we might have in the cyber area.

"And that leads into another big area, which is understanding the effects of a cyber or electronic warfare attack on our units. How does that affect the systems? How does that affect the operators? How does it affect the mission? We will need to look at a wider area of effects on both operators and operations in the event of a cyber or electronic warfare attack," he concluded. ■

ESSENTIAL RESEARCH AREA:

DISTRIBUTED AND COOPERATIVE ENGAGEMENT IN CONTESTED ENVIRONMENTS

By Craig Collins

Within the past several years, shifting global geopolitics have made it seem more likely that future military operations will be much different from those of the recent past. While Army leadership strives to prepare for an array of contingencies, the probability of wide-scale asymmetric warfare against poorly equipped insurgents appears to be on the wane, as potential adversaries come closer to matching the United States military in both numbers and capability.

In the future "multi-domain" battlefield envisioned by the Army, U.S. forces are likely to confront technologically sophisticated military adversaries, peer states, or proxies that can both use precision-guided, highly lethal munitions and counter traditional U.S. strengths by limiting access to space, cyberspace, and the electromagnetic spectrum. These peer-state adversaries have been studying U.S. strengths and devising ways of turning them into weaknesses. Continuous superiority in any domain is no longer assured.

In February 2017, the Army and U.S. Marine Corps published a white paper titled "Multi-Domain Battle: Combined Arms for the 21st Century," describing an approach, to be realized over the 2025-2040 time frame, for ground combat operations against a sophisticated peer enemy. One of the conclusions reached by the paper's authors was that, "Employing combined arms principles to create and exploit temporary windows of advantage across all domains is now a prerequisite for effective maneuver on the modern battlefield." In other words, ground combat units will need to be able to deploy capabilities in multiple domains – ground, air, and cyberspace, for example – with unmatched speed, flexibility, and scalability, to create and exploit enemy vulnerabilities.

One of the Army Research Laboratory's (ARL) recently announced Essential Research Areas – Distributed and Cooperative Engagement in Contested Environments (DCECE) – is a scientific program aimed at enabling mounted and dismounted American warfighters to achieve both focused and wide-area lethality while simultaneously frustrating or disrupting the lethal intent of their adversaries.

Scott Schoenfeld, PhD, ARL's Senior Campaign Scientist for Lethality and Protection, is coordinating the work of this ERA, which he says is aimed at capitalizing on the current explosion in intelligent systems technology. "Cheap, ubiquitous processors, networking, the internet of things – all these advances are allowing us to distribute intelligence into everything we need." The DCECE group of researchers hopes

U.S. ARMY PHOTO BY SPC. RANDIS MONROE

An M1 Abrams tank maneuvers through the National Training Center while an AH-64 Apache helicopter provides air support. While the Army has been fighting poorly equipped insurgents for almost two decades, it is more likely to face near-peer adversaries with more technological sophistication on future battlefields. The Distributed and Cooperative Engagement in Contested Environments (DCECE) ERA is aimed at enabling mounted and dismounted Soldiers to achieve focused and wide-area lethality while disrupting that of the enemy.

to bring this intelligent systems technology – the kind that enables Apple's Siri to recommend a restaurant for dinner, or Tesla's self-driving car to get you there – to the armor/anti-armor world.

The military's intelligent systems today are big and expensive – million-dollar guided missiles, for example, launched from $2 billion Navy destroyers. "So what we're really about," Schoenfeld said, "is bringing those kinds of intelligent systems into a world of very small, very smart, very low-cost munitions, in the hands of Soldiers."

The goal of the DCECE research team is to reassert U.S. military superiority – in a sense, using technology to give an individual Soldier the capabilities of a battle tank, a tank the capabilities of a brigade, and tactical units the full flexibility of combined arms.

DCECE solutions will incorporate more mature elements of existing weapons technologies, including weapon guidance and navigational sensing, submunitions, aerodynamics, and cyberwarfare. So far, progress in combining these technologies has happened in pieces: Bombs, rockets, and shells have been developed that break apart in the air over armored enemy units to reveal "smart" submunitions, smaller lethal units capable of destroying a target. Each of these submunitions is equipped with targeting sensors that can essentially hover or decelerate long enough to acquire a target, aim, and detonate a shaped charge or explosively formed penetrator (EFP) – basically a large metal bullet – at the target.

Such weapon systems, with submunitions activated by targeting sensors, were used to knock out Iraqi tanks in the early months of Operation Iraqi Freedom. They were devastatingly effective – and they're also completely outdated today. Against a sensor-rich peer adversary, such smart precision munitions simply wouldn't be smart enough, nor precise enough, to compete.

Toward Smarter Submunitions

ARL's DCECE team aims to provide U.S. ground forces with intelligent, scalable agents that can act as both weapons and shields. These agents will act in concert, directing, navigating, and maneuvering themselves to achieve collective effects and enabling U.S. fighting units to move wherever they wish.

In order to achieve these objectives, the DCECE group will build on the existing and developing technologies to develop submunitions that:

- Communicate and work together. Today's most sophisticated submunitions are limited in their ability to take orders and coordinate their effects. According to Schoenfeld, the submunitions of the future will function much differently, with communications equipment that will allow them to exchange and act on data collectively. "What's going to happen is that while they're in flight, they're communicating with each other and thinking collectively, not about a particular target, but about a particular mission."

The mission might involve a variety of yet-unidentified targets, so when a weapon is fired over an adversary's armored component, it will be able not only to locate and assign targets, but to prioritize them and direct themselves accordingly. Schoenfeld used the example of a shell containing six submunitions, communicating wirelessly, that comes upon an armored component with five soldiers and a tank. The submunitions could identify the tank – a target too resilient to be penetrated by one charge alone – and decide to focus and sequence their efforts to defeat the more dangerous target.

It may not be the case that every submunition in the group will require the same level of artificial intelligence – "It's the Army, and it's tactical weapons, so

A target tank is destroyed on the range by an explosively formed penetrator. Intelligent submunitions could follow one after another, hitting the precise spot on a tank's armor to defeat both passive and active defenses.

DOD PHOTO

these things are going to have to be cheap," Schoenfeld said. It may be that one group of submunitions will contain a command unit, in charge of a flock of less expensive, less intelligent drones. The "smart" round could use its sensors to find targets and send that data to its underlings; it could also make navigational decisions and send orders to the drones, which would go where they were told.

Navigation and wayfinding present perhaps the biggest challenges to agents that might work together this way: Whatever guidance system they use, it will have to be capable of making adjustments to compensate for factors such as wind, weather, or enemy movement – and it will have to be a networked system that can make these adjustments for multiple submunitions simultaneously. Existing navigation technologies come with their own shortcomings. GPS systems can be jammed fairly easily, and infrared heat-seeking sensors can be deceived. Laser guidance is more robust, but requires a degree of proximity to the target. The guidance systems necessary for distributed and collaborative engagement of a target will likely make use of multiple sensor modalities made robust by the multiple perspectives distributed amongst the flight formation.

These kinds of optical sensors will require a degree of artificial intelligence far beyond that of today's facial recognition software, or even the best self-driving car in existence – and the software used to run this sensing and navigation system will need to have built-in safeguards against sophisticated anti-access/area denial technologies, deception, and hacking.

In addition to a higher hit rate, such precision guidance has other benefits. It dramatically reduces the risk of collateral damage, and it conserves ammunition – which will save the Army money. A smart artillery round will likely carry an explosive warhead that's a small fraction of the size of a conventional unguided shell, and have the same destructive effect. Schoenfeld envisions a smart round capable of hyper-precision – zeroing in not only on the target itself, but on that target's most vulnerable spot – and capable of striking dispersed targets: a shell or two, for example, might be able to take out an entire platoon of enemy foot soldiers scattered along a ridgetop.

• Combine forces to achieve "cumulative lethality." Distributed and collaborative munitions will be both modular – an artillery shell or rocket-propelled grenade, for example, packed with a number of different lethal mechanisms – and scalable.

"If I have a certain explosive weight," said Schoenfeld, "and I want to tackle a light vehicle, there are things I can do inside the munition to shape the way it explodes. And if I want to attack a tank with heavy armor, I would shape the explosion differently." One way to do this, he said, is to change the way the charges or penetrators – the metal projectiles formed and fired at targets – are formed.

Today's submunitions, once in the air, typically fire a specific kind of penetrator – a metallic liner that's both shaped and propelled by an explosive charge – into a conventional bullet shape. Depending on the target, Schoenfeld said, that penetrator might need different dimensions – to pierce armor with maximum concentrated force, for example, or to generate fragments over a wider area. "Do I keep the metal together and shape it into a very compact ball," Schoenfeld said, "or a highly elongated penetrator to go through some thick armor?" Future munitions will require an onboard intelligence that can both sense the type of penetrator needed and program a detonation that will shape it.

A group of networked submunitions could achieve "cumulative lethality" – working together to fire the right kind of projectiles, in sequence, to defeat a target. An individual submunition, for example, may have the capability to focus its explosive power to penetrate an inch of steel. If six of them are shot into the air within a single shell, they will need to coordinate their efforts. "They might see that there's a target out there, a tank armed with five inches of steel," said Schoenfeld. If they all target it and fire

independently, the likely result will be a big one-inch scoop taken out of the armor. "What I want to be able to do is fire five of them down the same hole, one after the other."

This method of attack could also be used against a target that uses countermeasures. If the target has the equivalent of five inches of steel armor, and there are six in a group, Shoenfeld said, "I'll send one first, and let the tank waste its countermeasure – and then I'll send in the other five."

• Maneuver independently – and collectively. For the most part, today's cutting-edge submunitions, once they're unpacked from their bomb or shell casings, hover in place or dangle from drogue parachutes before firing their payloads. They have no ability to maneuver themselves. Against a sophisticated adversary with countermeasures, they'll have to do better – to coordinate themselves, for example, once they've agreed to gang up on a high-value target, in order to line up and fire in sequence. "And since they're maneuvering towards the heart of the target," Schoenfeld said, "they might even have to maneuver to avoid whatever the enemy does to defend themselves, to try to shoot them down."

All the hardware needed for these capabilities will have to fit into a platform allowing a volume of probably not more than a couple of cubic inches – and it will have to be robust enough that it can either be used within a projectile that is dropped, launched on a ballistic trajectory, or fired directly at targets. In other words, the onboard electronics will have to be able to withstand extreme *g* forces and to scan, process, maneuver, and fire in milliseconds.

Small agents flying fast and close together present a set of aerodynamic challenges. Things that fly disturb the air around them – which is why aircraft avoid flying close together. If maneuverable submunitions are launched from the same casing, they'll have to be smart enough to counteract the aerodynamic effects caused by their proximity.

• Play defense. In the six-bullets-against-a-tank analogy above, one bullet sacrifices itself by drawing the tank's countermeasures. This sacrifice is still, essentially, an offensive feint. Against a peer adversary with its own distributed and collaborative munitions, an armored unit must be able to defend itself against the same kinds of attacks. "We have to be able to protect against multiple near-simultaneous impacts, volley fire, and things like that," Schoenfeld said. The submunitions of the future will be flexible enough to adopt this defensive posture – a Soldier, for example, might shoulder-fire a missile into the air above a battlefield; the missile casing would drop away to reveal the submunitions; and those submunitions could then deploy to become countermeasures.

■ **A rocket-propelled grenade (RPG) round is defeated by the FCS Active Protection System (APS) for Manned Ground Vehicles during a test. It was the first time that any vertical launch APS defeated an incoming RPG while mounted on a moving vehicle. ARL is working to develop submunitions of the future that can protect friendly forces on the battlefield as well as destroy the enemy.**

PHOTO COURTESY OF FCS

These countermeasures could be either kinetic – essentially, firing chaff to confuse, or penetrators directly at the adversary's submunitions to shoot them down – or non-kinetic applications such as jamming or disrupting technologies. Lasers can be an effective non-kinetic countermeasure, Schoenfeld said, creating thermal and disruptive effects on the incoming round. Electronic warfare – propagating radio frequency waveforms, for example, that can interact with the electronics of an adversary's system – could also disrupt an enemy attack.

In the "protection" half of ARL's lethality and protection campaign, researchers such as Schoenfeld create devices for what's called "target interaction": pieces of metal, or explosives, or electricity that can be prepositioned to intercept and neutralize an incoming projectile. Each of these countermeasures performs a very specific prescribed action. "But if suddenly those have the kind of intelligence where they can see what is coming at them, they could calculate what they need to do and make up their mind about the best way to manage that threat," Schoenfeld said. These elements themselves could report back to Soldiers when they've encountered something new or unexpected. "In Iraq we were confronted with weapons we weren't prepared for," he said. "And so rather than having to capture those weapons, bring them back here, and create a research program to figure out how to neutralize them, I want those armors to be able to do that up-front."

These requirements, Schoenfeld said, ask a lot of future artificial intelligence: It must be smart and fast enough to recognize a threat, formulate and coordinate a collective defense, and provide a split-second reaction in order for these agents to counter attacks on Soldiers, armor, platforms, and weaponry, including themselves.

To help develop the distributed intelligence necessary for such capabilities, the ARL formed a Collaborative Research Alliance (CRA) in 2017, aimed at extending the reach, situational awareness, and operational effectiveness of large heterogeneous teams of intelligent systems and Soldiers in contested environments. The Distributed and Collaborative Intelligent Systems and Technology (DCIST) CRA is a consortium led by the University of Pennsylvania, and includes the ARL and laboratories from several other universities. The CRA's research will focus on three key areas of research: distributed intelligence, heterogeneous group control, and adaptive and resilient behaviors.

Schoenfeld and other DCECE researchers aren't developing a specific weapon; they're developing the building blocks necessary to build a variety of different weapons. They're also not working alone; a glance at ARL's other Essential Research Areas reveals the intersection of the research done by several others – including Human-Agent Teaming, Cyber and Electromagnetic Technologies for Complex Environments, and Artificial Intelligence and Machine Learning – and the DCECE group. "We work very closely together," said Schoenfeld, "to make sure these things stay connected." These connections may be difficult to see now, given the way most battles are fought today, but within a few decades, or even years, they'll be impossible to miss. ■

ESSENTIAL RESEARCH AREA:

TACTICAL UNIT ENERGY INDEPENDENCE

By Craig Collins

Brigade combat teams (BCTs) will remain the Army's primary fighting formation through at least 2040. In the future peer contested multi-domain battlefield, BCTs will be required to operate at high operational tempos in decentralized, dispersed and semi-independent fashions requiring them to be highly mobile and adaptable to the changing battlefield. Reducing the overall power consumption and logistics demands will be a key enabler in increasing operating range and period between replenishments to realize improved endurance for extended operations. Achieving these dispersed and potentially longer duration maneuver missions will require more energy dense and efficient organic assets, more adaptable systems and increased ability to operate in degraded conditions, better energy awareness and management across all assets, and the development of autonomous ground and aerial distributions systems to provide adaptable and flexible maneuver operations.

Developing BCT overmatch abilities to out maneuver and out endure adversaries across multiple and complex domains, to include dense urban areas, extends down to the company, platoon, and squad level which are the base elements for organizing tactical units for combat operations. This is placing a priority on technologies that lighten the Soldier load and provide options for increased mobility, endurance and lethality for small tactical units operating over widely dispersed, complex, and contested environments.

Over the past two decades, more portable and wearable technologies have been a force multiplier for tactical units and dismounted Soldiers. But adding these increasing capabilities – in sensing, situational awareness, communications and other areas – have come at a steep price. According to the U.S. Army Maneuver Center of Excellence (MCoE) at Fort Benning, a platoon in the 1991 Gulf War needed 1,740 watt-hours (Wh) of energy to complete a 3-day mission. A decade later, at the outset of Operation Enduring Freedom, that energy requirement had increased slightly, to 2,076 Wh for a 3-day mission. Today, a platoon's energy estimated demand for a 3-day mission is a staggering 31,305 Wh.

U.S. AIR FORCE PHOTO BY STAFF SGT. CHRISTOPHER HUBENTHAL

This increase in energy demand has not been matched by innovations in the ability to generate power, convert and store energy, and manage and distribute power. The battlefield of the future will become increasingly digital and network-centric, with new generations of sensing, weaponry, targeting, fire control, communications, and even unmanned air and ground systems (UAS and UGVs) adding to the energy demand of tactical units. Thus, the energy burden at the tactical edge isn't likely to wane anytime soon.

Army tactical units (in this context, units of company size or less, typically numbering less than 150 individuals), operating in the multi-domain battlefield of the future, will include unmanned and intelligent systems. The overall net unit energy balance will be both helped and hindered by the integration of UAS and UGVs at the company, platoon, and squad level. The emerging robotic and autonomous systems (RAS) strategy enables human-machine collaboration across all mission areas by extending the area and time over which a force can be effective. Robotics consists of ground robotics, autonomous systems, and small unit power that enables Army formations greater situational understanding, protection, mobility, and lethality. Near term plans

■ U.S. Army Pacific Soldiers of the 25th Infantry Division move in formation while controlling unmanned vehicles as part of the Pacific Manned-Unmanned Initiative July 22, 2016, at Marine Corps Training Area Bellows, Hawaii. The proliferation of more portable and wearable technologies, as well as unmanned systems, has vastly increased small units' energy demands.


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Sgt. Brandon Marshal, a signal support systems specialist in the 8th Brigade Engineer Battalion, 2nd Armored Brigade Combat Team, 1st Cavalry Division, launches a Raven unmanned aerial vehicle during his final certification as a UAV operator. While unmanned systems are necessary to provide increased situational awareness for small units, they also add to the overall power demands of the unit.

U.S. ARMY PHOTO BY STAFF SGT. JOHN HEALY

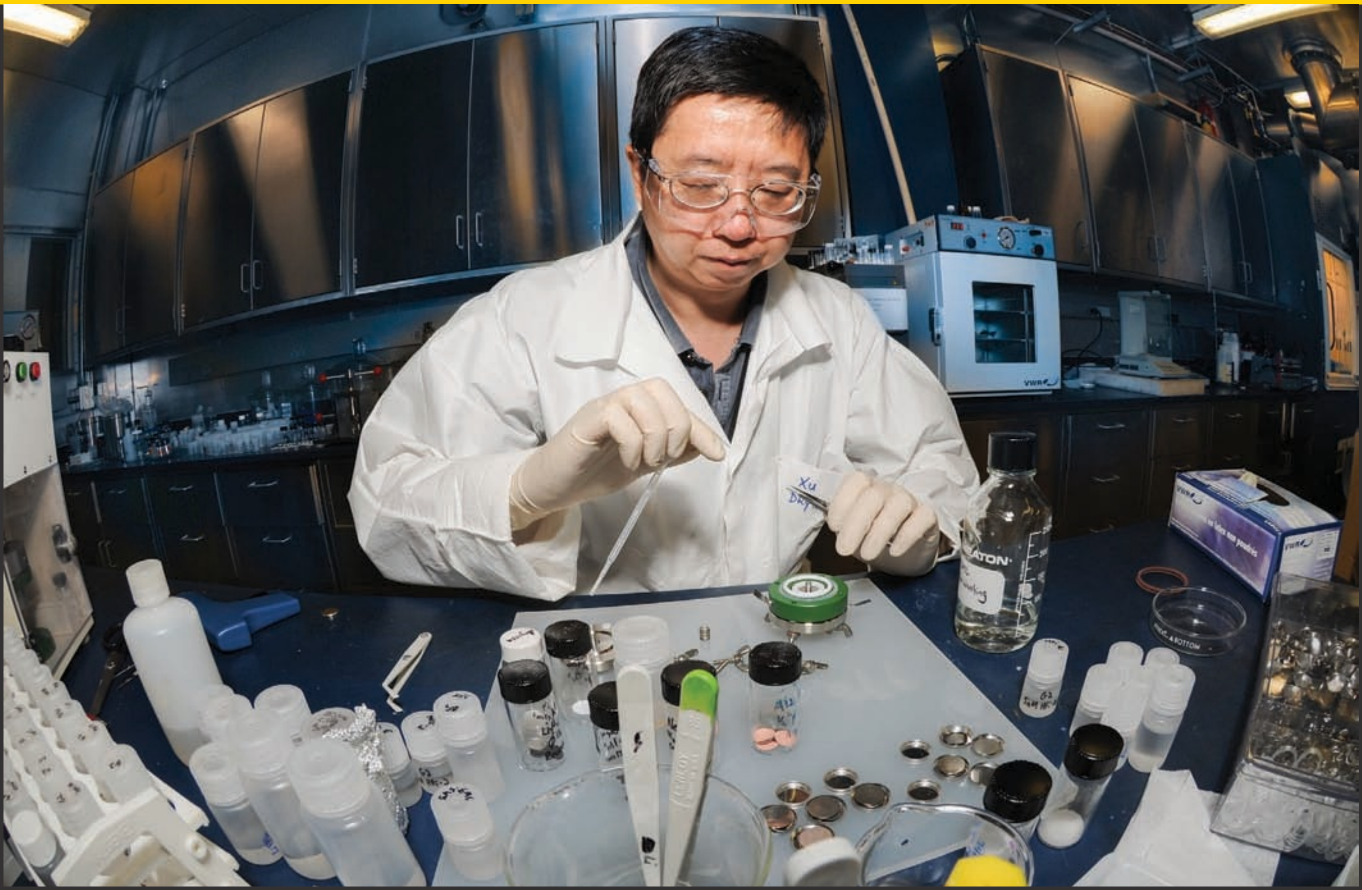
incorporate Group 1 ISR (intelligence, surveillance, and reconnaissance) aerial platforms, such as the Puma at the battalion/company level, the Raven at the company/platoon level, the short-range micro at the platoon level, and the Soldier borne sensor at the squad/team level. All of these aerial systems utilize battery power and have mission duration ranging from a few hours to less than 20 minutes, adding to the overall power demand of the unit. Some applications are looking at tethered UAS to overcome the power challenges for these systems, but these are only good for local or stationary applications.

The RAS near term strategy also includes ground platforms such as the Squad Multi-purpose Equipment Transport. The larger version has a planned goal to carry 1,000 pounds to lighten the Soldier load, have a range of 96 km while carrying additional energy sources without resupply for up to 72 hours, be able to off-load 3 kW of electrical power, and be capable of recharging all rechargeable batteries in a dismounted Army infantry platoon. Systems like this coupled with research on exoskeletons and on-going S&T efforts looking at autonomous aerial and ground resupply could have a significant impact on the mobility and ability to do long duration sustained operations for small tactical units. Adequate power supply and energy management will be become critical enablers for the battlefield environment envisioned for the future.

The importance of developing and integrating novel technologies for sustained operations has compelled the Army Research Laboratory to designate Tactical Unit Energy Independence (TUEI) one of its Essential Research Areas (ERAs). Brett Piekarski, PhD, Senior Campaign Scientist for ARL's Sciences for Maneuver Campaign, is coordinating the effort to develop S&T plans and strategy to assist tactical units in operating lighter, integrating with RAS and becoming more mobile, consuming less energy, and operating for greater periods of time without energy resupply.

Absolute energy independence for such tactical units is a futuristic aspiration, Piekarski acknowledged. "But we want that kind of futuristic goal to really drive innovation. If you look at the future concepts for the multi-domain battlefield," said Piekarski, "we expect to be in a peer-contested environment that won't allow you to set up a forward operating base. You're going to have to move. Your opportunities for resupply will be limited. You can think of this ERA as our effort to increase lethality by lightening not only the physical but the power load for the tactical unit – the idea being to increase maneuverability and endurance while ensuring a sustained energy balance which does not add to the overall logistics burden back to the BCT."

A key component in achieving this goal is the development of an intelligent energy management architecture which includes a hub that could reside on a future highly mobile and agile autonomous squad support platform. Today and into the near future, this energy management is done at the local and individual Soldier level and tends to be single point and manual in nature (e.g., Soldier plugs into an APU on a vehicle to recharge his batteries at the end of a mission). The current



ARL PHOTO BY DAVID MCNALLY

■ **Kang Xu, an Army Research Laboratory scientist, is one of the inventors responsible for a 30 percent increase in energy density in safer, highly conformable li-ion batteries.**

methods are also inflexible in relation to their capability for power distribution as they have no understanding of the overall energy balance across the systems and no efficient method to impact that balance. A future intelligent energy management system would have increased energy awareness (of energy sources, storage, and demand) across all levels from the BCT down to the individual Soldier, would be flexible to handle future dispersed and highly mobile operations where elements are coming into and out of the energy network, and it would have the ability to inform, generate, and redistribute energy when and where it is needed to more effectively use the organic power already being generated or available within the collective system. The system would also be intelligent enough to manage both autonomous aerial and ground assets to coordinate the safe, timely, and energy efficient delivery of supplies to distributed and detached units. It would also be able to integrate the unit's energy needs and supplies into the overall intelligent energy management network when not operating detached from the larger operational elements.

A goal would be to integrate the system across all command structures from the BCT down to the individual Soldier. At Soldier level this would entail a Soldier worn system that can autonomously monitor the energy sources and demands at the Soldier component level and intelligently redirect energy as needed and optimize energy usage. At the squad or platoon level, this system could be integrated onto a future highly mobile squad level autonomous asset. This asset could move with the tactical unit, be a source of energy for the unit, and it could monitor and redirect power across the unit as needed to minimize the chance for any single-point failures (Soldier or platform running out of power) while also increasing the efficiency and duration of the overall unit. It would employ emerging Artificial Intelligence techniques to learn and predict the energy profiles of the individual and overall unit, the technologies employed, and the energy landscape of the operating environment, and modify energy usage and distribution in order to complete the mission profile. This AI could unburden the Soldier from energy monitoring and decision-making. Future systems would be expandable beyond the small unit to all levels of command and be adaptable to the changing operational and energy demand environment.

"These are futuristic concepts," said Piekarski. "We're looking at innovative approaches, in order to move us toward energy independence." This effort would require new technology developments in artificial intelligence and machine learning (AI/ML) methods for energy awareness and distribution, new technologies for efficiently and rapidly transferring energy between systems and Soldiers while on the move, and technologies for rapidly rechargeable batteries and batteries integrated into multipurpose structures for lightening the load. It would also leverage the development of highly mobile, stealthy, and long endurance autonomous systems that can traverse any terrain, leading to self-sustaining robotic operations and the integration of RAS with small tactical units, increasing range and endurance for the overall unit, while reducing the logistics burden.

In order to achieve the overall vision, the TUEI ERA is also leveraging many ongoing research efforts to improve and realize a self-sustaining energy balance by enabling self-sustaining autonomous systems, increasing flexibility in collecting and using

University of Pennsylvania researchers demonstrate a successful perching technique where an autonomous quadcopter attaches itself to a log.

ARL PHOTO BY JHI SCOTT

locally available fuel/energy sources through development of thermophotovolatics and multi-fuel tolerant hydrocarbon based engines, increasing the energy density of Soldier wearable and conformable batteries, augmenting Soldier and platform energy via alternative and energy scavenged power sources, mitigating high power drain components (such as Soldier radios, sensors, and computing) via low power electronics, and enhancing mobile energy operations and flexible distribution via near and far range wireless power transfer.

The autonomous systems developed for future expeditionary units will create operational challenges if they add to the unit's energy burden, so everything about their concepts and designs, including materials, propulsion systems, power sources, operation and maintenance, is aimed at maximizing efficiency – and ultimately at making them self-sufficient. ARL's Microsystems Mechanics Team, led by Christopher Kroninger, is investigating ways to make smaller portable platforms more energy efficient, with the ultimate goal of complete self-sufficiency. The team is investigating the use of a small hand-held UAS that can be carried by a small tactical unit and deployed to provide situational awareness. The typical quad-rotor UAS that will soon accompany tactical units can fly unsupported for only about 20 minutes.

To enable these smaller organic UAS systems to provide situational awareness, unsupported, Kroninger said the team is focusing on two performance aspects – structural adaptation and behavior – and looking to nature for inspiration. "If you look at a bird of prey when it's loitering," said Kroninger, "flying slowly, looking for prey, its wingspan is wide. But when it goes into that dive, to actually catch that prey, it wants to go fast, so it pulls in its wings, reduces its wing area, reducing drag, so it can move rapidly. That's an example of structural adaptation." Kroninger's team is working on models that will allow a fixed-wing UAS to achieve similar efficiencies while in flight.

Birds use several other tactics to conserve energy: They can glide over an area, rather than hover in place. They can ride thermal currents upward without working to propel themselves. And they can perch – which uses almost no energy. A UAS with the ability to perch would be huge, Kroninger said: "If you're providing situational awareness, it makes a lot of sense to stop flying. If you're a rotorcraft, just sitting there hovering and staring, you're wasting a lot of energy."

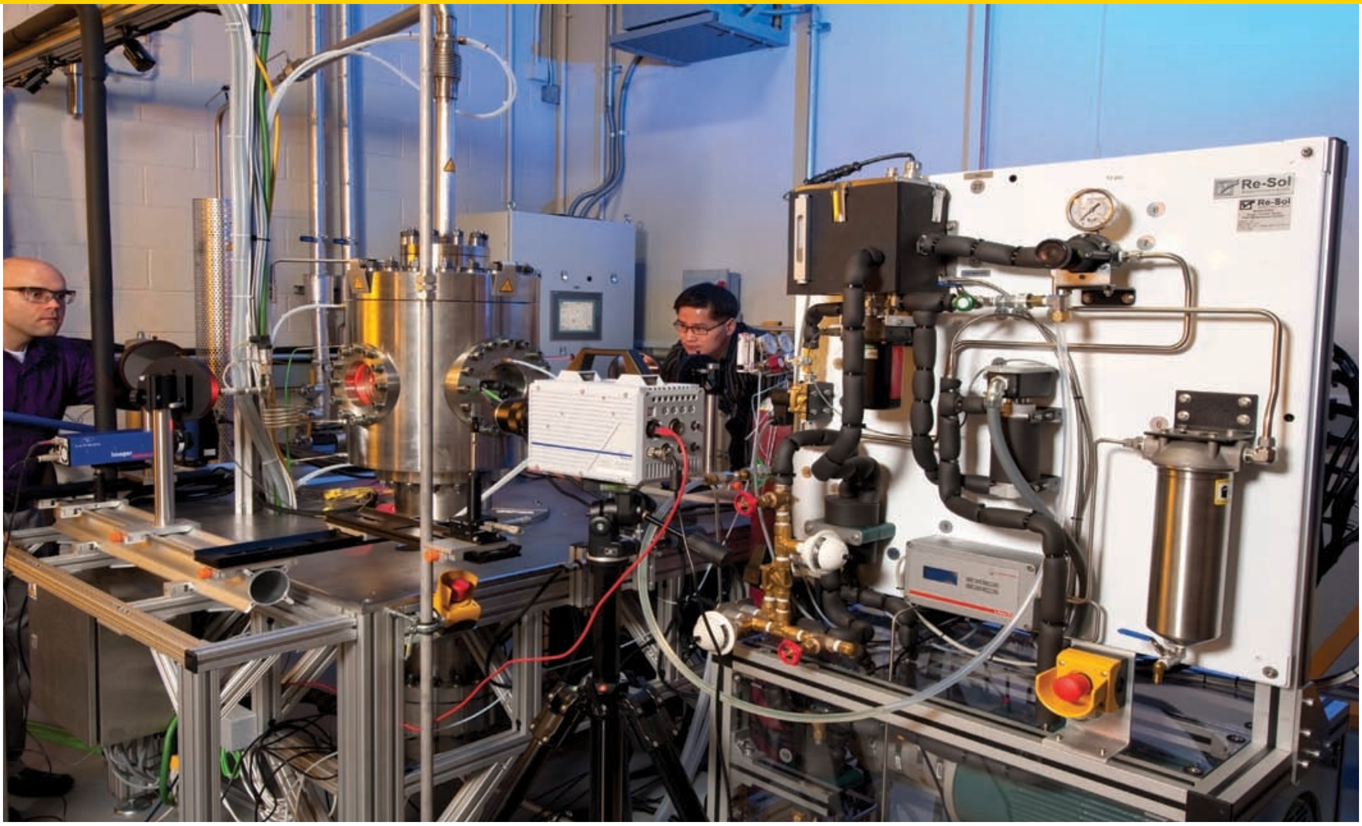
Significant energy savings may also be achieved by developing robotic and autonomous platforms capable of intelligent energy-aware maneuver. The Chief of the ARL Mechanics Division Chief, Jaret Riddick, PhD, leads a team of researchers that is pursuing new science to enhance the sustainability and reliability of future vehicle platforms. "The concept is to emplace and embed sensors to monitor material state," said Riddick, "in an effort to detect degradation in critical components prior to the development of damage. Awareness of damage precursors may be utilized to operate vehicle platforms intelligently, mitigating the onset of damage, extending the life of critical components, and reducing the need for unscheduled, labor-intensive maintenance procedures." In the future this type of intelligent vehicle operation can be leveraged to achieve intelligent highly efficient energy-aware maneuver by linking vehicle performance, damage-state awareness, and energy demand with route and mission planning.

Scavenging fuels is another way to increase mission duration in the field. According to Mike Kweon, PhD, Chief of the ARL's Propulsion Division, research in this area is focused on developing engines that will run on fuels containing hydrocarbon molecules with a wider range of carbon numbers. "Lighter" fuels, such as natural gases, have carbon numbers from C1 to C4. Gasoline typically contains hydrocarbons in the C4-C10 range; kerosene and aviation fuels are generally in the C4-C19 range; diesel fuels are generally within the C8-C21 range; and heating oils tend to fall into the range of C15-C22.

Most of today's internal combustion engines are pretty specific about the carbon numbers they'll accept, Kweon said, and different tactical platforms – ground vehicles, fixed-wing UAVs, rotary-wing UAVs, and unmanned ground vehicles and robots – each have their own requirements. "The PMUAS [Program Manager, Unmanned Aircraft Systems] and the MCoE want engines that can run on any fuel," said Kweon. "In our case, we want to develop engines that can burn fuels with carbon numbers from C1 to C20. That's a wide range of fuels that includes the gasolines, the alcohols, the jet fuels and diesel.

The Soldier is the building block of a tactical unit, and much of the ARL's current work in creating efficiency – both on the demand and the supply sides of the energy equation – is focused on the individual Soldier.

On the supply side, ARL has significant ongoing efforts in conformal wearable batteries (CWBs) – the thin, lightweight flexible batteries that integrate with the Soldiers'



Researchers in ARL's Spray Combustion Research Laboratory explore combustion physics toward realizing multi-fuel-tolerant engines.

ARL PHOTO

body armor, recently developed by the Army's Communications-Electronics Research, Development and Engineering Center (CERDEC) – are currently capable of providing about 60 percent of the portable power needed for a platoon's 3-day mission. Even today, before the imminent surge in tactical power demands, expeditionary units need not only more efficient energy-consuming devices, but also portable sources of renewable energy that don't depend on the weather or time of day, as solar and wind applications do.

One promising alternative supply technology in the early stages of development is thermophotovoltaic (TPV) energy converters, which do not need direct sunlight to generate electricity. TPV energy converters absorb infrared radiation – heat – and convert it to electric current, even in the dark. "What you're doing is burning fuel to heat a surface to emit energy," Piekarski explained, "and then you're using photonic bandgap material to optimize the spectrum of the emitted light coupled with a photon detector to convert that energy to electricity. It's sort of like a solar cell, but instead of using the sun we're using another energy source." Heat sources under investigation include powerful hydrocarbon fuels such as propane or JP-8, a kerosene-based jet fuel. Today's prototypes don't look much different from the fuel canisters used by recreational campers – but these are just the beginning. TPV energy converters, because of their greater energy density have the potential to reduce the weight carried by a Soldier dedicated to energy (batteries) by over a factor of two as a near-term goal when compared to rechargeable battery specific energy (195 Wh/kg for the military BB2590 lithium ion rechargeable battery).

Future TPV systems, Piekarski said, might be developed in a way that will allow them to be worn like conformal batteries, plug-and-play fuel cartridges that fit inside a Soldier's flak jacket – or they may be scaled up to the squad or platoon level, comprising a bigger central fuel source that could be used to recharge batteries or directly power some devices. A major emphasis for these future systems is multi-fuel operation to be able to operate off of scavenged fuels.

On the demand side, according to Romeo del Rosario, PhD, Chief of ARL's Electronics Technology Branch, the biggest power drain for the individual Soldier is the radio and communications equipment he or she carries on a mission. All told, radio equipment accounts for more than 86 percent of the power consumed by an expeditionary Soldier, requiring more than 9 watts for a 72-hour mission.

The problem of power consumption for Army radios is much more complex than it is for civilians who use smart phones – the tactical environment is, by definition, an unregulated and contested space, requiring a degree of permanent sensing and data throughput. "You can't turn off your eyes and ears," said del Rosario. "So there's always going to be some kind of drain. The most important question we're asking is: Why is the radio and communications equipment draining so much power?"

Several components within a Soldier's radio, del Rosario explained, draw a lot of power, and two of the biggest drains are the radio frequency (RF) front end, which amplifies a signal and transmits it over the antenna, and the field-programmable gate array (FPGA), which is essentially the radio's logic circuit. Many of these logic boards were once application-specific prototypes that proved effective enough that contractors simply incorporated them in communications equipment without modification. "As long as the power budget isn't your biggest concern," said del Rosario, "that's what's going to happen."

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A thermophotovoltaic (TPV) energy converter glows inside an ARL/MIT microreactor. Thermophotovoltaic energy converters absorb infrared radiation and convert it to electric current, even in the dark.

ARL PHOTO

Now that energy consumption is one of the most significant concerns for tactical units, the way these components are built and interact will be a major focus for del Rosario and his team. “We’re doing things at the materials level, the circuit design level, and at the architecture level to reduce this power drain,” he said. Probably one of the team’s biggest undertakings is what it calls heterogeneous integration – combining all the power-draining components inside today’s radios into a single silicon chip that will draw from 3 to 10 times less power than the components draw separately. “Imagine your cell phone charge lasting 10 times as long,” said del Rosario. “You could go a week with no loss in functionality. That’s what we’re going for.”

In the case of digital communications over a wireless network, edge processing – optimizing cloud computing systems by performing data processing close to the source of the data – is one example of how the energy demand for communications could be reduced. For other applications, investigators are looking for opportunities to use solid-state devices and components – which serve the same function as electromechanical components, but have no moving parts, and therefore consume less energy. Personal electronic devices (PEDs) carried by Soldiers are expected to take on more functionality in the future, perhaps playing a role in emerging electronic warfare and counter-UAS technologies. One of the ARL’s near-term goals is a PED with 5 times greater efficiency, along with a 30 percent increase in a Soldier’s portable energy density.

Finally, ARL is also exploring technologies for enabling wireless power transfer and energy/power management among Soldiers, sensors, platforms and energy sources within the unit. Sarah Bedair, PhD, who leads ARL’s Microsystems Power Components Team, has worked for nearly a decade in the development of component technologies that will improve the efficiency of wireless power transfer. Some of these are “near-field” or non-radiative technologies, which transfer power using magnetic (inductive coupling, using coiled wires) or electric fields (capacitive coupling, using metal electrodes). Bedair and her ARL colleagues are experimenting with interconnected receiver arrays that have achieved efficiencies more than 4 times greater than a single receiver transducer alone. Bedair’s team is also working on “far-field” or radiative techniques, also known as “power beaming,” in which power is transferred in beams of electromagnetic radiation aimed at a receiver at km level distances vs less than a meter for near field techniques. If unmanned vehicles could be fitted with an efficient receiver, it could operate as long as a unit is able to generate and transmit power.

The ARL anticipates that these innovations will someday enable a tactical unit to generate and store as much power as Soldiers need for their missions – a “net-zero” unit, capable of creating as much renewable energy as it consumes. Whether missions last three days, seven days, or indefinitely, the Army will be better equipped to deploy an expeditionary mobile force, under extreme, remote and perhaps unforeseeable conditions.

Sensors attached to a translucent model skull are used to measure explosive shock velocity and pressure at the Army Research Laboratory Weapons and Materials Research Directorate at Aberdeen Proving Ground in Aberdeen, Maryland, March 9, 2016. Data captured by the sensors are used to assist studies in traumatic brain injuries.

DOD PHOTO BY EJ HERSOM

ESSENTIAL RESEARCH AREA:

MANIPULATING THE PHYSICS OF FAILURE FOR ROBUST PERFORMANCE OF MATERIALS

By Scott R. Gourley

In meeting its mandates to support tomorrow's Warfighters, the U.S. Army Research Laboratory (ARL) conducts essential research into "manipulating the physics of failure" to enhance the robust performance of military materials.

ARL is very well known for its protective materials and protective schemes, as well as lethal mechanisms and weapons," explained Dr. Adam Rawlett, Chief Scientist in ARL's Weapons and Materials Research Directorate (WMRD). "We have a significant history about really understanding how to protect Warfighter assets, whether that's the Warfighter themselves or the vehicle that he or she is driving, enabling, etc."

Rawlett said that much of that Essential Research Area is focused on areas of "dynamic fracture" and "dynamic failure."

"It is really about how materials break under high strain rates and high stresses," he said. "If you talk about the commercial side or research directed toward the general public, a high strain rate is something like a car crash or two football helmets colliding. But here at ARL we're talking about impact forces that are orders of magnitude greater. Most of industry and most of the general public is really not interested in how things break at these high rates. So the Army has dedicated significant resources, time, talent, and treasure – again over the last 50-plus years – to really understand how things break in military environments."

Rawlett said that an understanding of how things break can translate to better protective schemes in areas like vehicle armor or Soldier body armor.

"Conversely to that, at times we have the need to project force. If we have a mature understanding of how things break, we can apply that to lethality scenarios. For example, we have developed and demonstrated significant expertise in making bullets: from small arms bullets all the way up to long rod penetrators fired from Abrams tanks.

"So we are not only experts at mechanistic solutions for defeating projectiles – whether they're for protection of vehicles or the individual warfighter – but also the materials and mechanisms for defeating our adversary's armor solutions," he added.

Noting that ARL conducts "robust program in all material classes," Rawlett said that considerable focus is directed toward metals and ceramics.

"Armies around the world utilize significant amounts of metals – and more recently ceramics – as major elements of land vehicles and personnel protection systems," he began. "So we are really trying to understand those materials as they undergo deformation due to a ballistic or blast type of event. We really need to understand how the armored vehicle or human will perform under those rates and those stresses."

He continued, "We also look at soft materials; whether it's composites or organic materials like polymers. Again, we are a laboratory that has a significant amount of knowledge on materials, specifically looking at how materials interact at these really high loading and strain rates; the ones that are typically beyond what the general public may be interested in."

While emphasizing that ARL keeps its focus on long-range technologies, Rawlett acknowledged several feedback loops that help to advise and inform research projects to reflect lessons currently being learned on today's battlefields.

"Our job is to serve the Warfighter," he said. "So it's very important that we have a direct line of communication, not only with Army Warfighters, but also with the other services, because we also work with the Marine Corps, Navy, and Air Force. When it comes to materials, there is a lot of overlap between the services and we work with a lot of great folks within the other services."

He said that the Warfighter input has ranged from reports of ongoing events in theater to possible problems being encountered.

U.S. ARMY PHOTO BY SPC. ROGER HOUGHTON

U.S. Army Soldiers of 5th Squadron, 73rd Cavalry Regiment, traveling in M1114 High-Mobility Multipurpose Wheeled Vehicles (HMMWV) equipped with Interim Fragmentation Kit 5 armor kits, which ARL helped develop.

U.S. AIR FORCE PHOTO BY STAFF SGT. DENORIS A. MICKLE

"By all means we have direct lines of communications with the folks," he said. "And we also work with the U.S. Army Training and Doctrine Command [TRADOC] community as well. TRADOC studies long-term futures for the Army, looking at how the Army will fight in the future, and breaks it down into capabilities that they would like the Army to have – whether it's for 2030 or really deep future 2050 time frame. And we assist them in helping break down what science can do and what scientific questions or discoveries will help enable that future and ensure what they refer to as 'future readiness.'"

Emphasizing the Essential Research Area "tagline" of "detect, characterize and manipulate the physics of failure to create disruptively capable structures that are portable, available, and adaptable," Rawlett said that the underlying efforts explore materials and systems "that can sense and adapt at the speed of the fight."

"Think about a lightweight and flexible armor that can 'sense' impending danger," he offered. "To react to the speed of the fight first mitigates the danger and then returns to the normal state. Think of it as kind of a smart armor or material system that can remain flexible, allowing different missions to occur, but when it senses impending danger, it changes its state in such a way that it will prevent that danger from causing harm to the vehicle or the human. And then it will return to its normal environment."

He elaborated, "Consider a flexible armor that will allow the operator to move freely in a normal state. If I hit that with some type of ballistic threat, the bullet may go right through that flexible garment. But now think about a garment or armor that realizes it's in danger and creates a new state, becoming super hard or super tough, being able to mitigate that danger before returning to its normal state."

Switching scenarios, Rawlett offered a "converse" scenario involving a fired projectile.

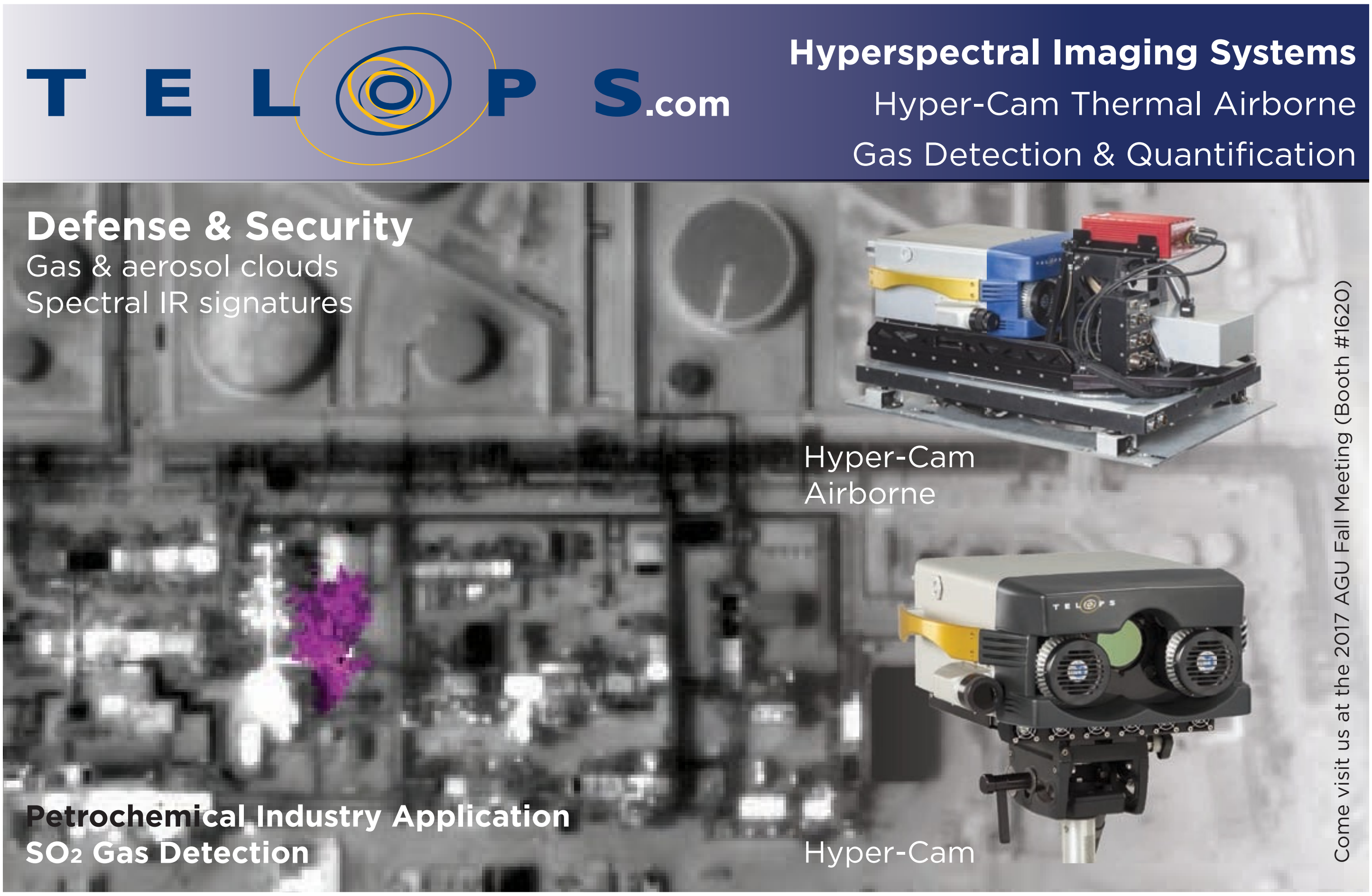
"A gun or rocket projectile could be fired, sensing not only the intended target but also the protective scheme on that target," he said. "It could then adjust its effect in real time, at the speed of fight, to defeat myriad target sets. You could have a launched projectile that 'understands' if it needs to take out a hard target and can then program itself to do that. Or, if it ascertains that its intended target is a crowd of hostile Soldiers, it could change its effect in transit.

Reiterating that ARL efforts are focused on a "deep future" vision of the 2050 time frame, Rawlett said that the future vision needed to be broken down into "bite-sized chunks" that can be explored today.

Within this Essential Research Area, that process has created three identified "gap areas" with a number of subordinate opportunities.

The first identified gap area involves understanding the physics of failure.

"This really involves understanding how materials fail at those high strain rates," Rawlett said. "And it is further broken into numerous subordinate categories. For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■ **Ceramic armor plates for Soldiers' body armor. In addition to helping develop existing body armor, ARL scientists are researching ways to improve the armor of the future through studying the physics of failure.**

U.S. ARMY PHOTO BY STAFF SGT. IAN SHAY

example, stepping down a level, we are looking at 'probing at extreme conditions' to see how materials fail at various micro-scale levels."

Citing collective ARL research conducted at the Department of Energy's Argonne National Laboratory, Rawlett highlighted the importance of "peering into the materials at the sub-micrometer scale" to look at how failure occurs.

Equipment available at the laboratory includes the Advanced Photon Source, which provides a high-energy synchrotron X-ray beam for scientific research.

"With a better understanding of how things break, we can better understand how to predictively model and eventually build those protective systems," Rawlett continued.

"Also, understanding in physics and probing at the extreme scales, we also want to have the ability to create a more predictive model," he added. "Using the Department of Energy facility can be expensive and time consuming, so we are looking for a way we can utilize computer modeling to really try to elucidate those structural property relationships and really try to understand how things break. Because if you do it on the computer, you can do it quicker, easier, and cheaper, assuming the computer code has been validated against experimental data."

In addition to examining the physics of failure on various levels, Rawlett said that ARL has focused considerable efforts on the concept of "scale bridging."

"ARL, in general, is very good at computer modeling," he explained. "And that can span from the 'engineering scale' modeling of an entire Abrams tank to the smallest scales where you are really looking at atoms and how materials fail on the atomistic scale. And in between those there are things like the mesoscale, where you are looking at things like grain boundaries. But when you're looking at dynamic fracture, multiple scales are important in how they influence each other. It is very, very important to know how things will break. And so we are part of an academic community that is very interested in scale bridging from that engineering scale down to the mesoscale, down to the atomistic scale."

Rawlett offered the example of body armor being struck by a bullet.

"When the bullet hits the body armor, cracks start to form in the ceramic plate," he began. "That's at the finite element scale. But if you go down one level, to the mesoscale, you see the way the ceramic is starting to comminute– to break up into small pieces. That comminution affects how the cracks will propagate into the body armor. And if we can have a greater understanding of how the cracks will affect the rubblization, and vice versa, we can have a more sophisticated understanding of how we can improve body armor.

"So scale bridging is a pretty important factor if we ever want to do truly predictive modeling," he added.

In addition to better understanding the physics of failure, Rawlett said that another gap area focuses on exploiting and manipulating the material failure at relevant time and length scales.

"This is where the science fiction really starts," he said. "Right now we have materials that are passive. Those are things like a chunk of ceramic, for example, or a chunk of metal or a chunk of polymer. So how can we make them smart? What I mean by that is, how can these materials be manipulated at the right temporal – meaning time – and spatial – meaning space –scales? In other words, how can we get them to change while the ceramic is being impacted in such a way that it has the ability to defeat that projectile?"

"Can we discover new elusive phases of condensed matter, like non-equilibrium states or high-entropy solids? Can we intentionally induce phase changes in materials?

"Again, that thinking is focused on trying to understand how we can manipulate materials at the right time scales to be able to effect the ability to better protect our assets, whether it's the Warfighter or the vehicle."

The third major gap area involves synthesis and processing.

"The bottom line is that first, we need to understand material failure," Rawlett asserted. "Then we need to learn mechanisms to exploit that failure. And third, we actually need to build those materials. So, the third gap area involves the synthesis and processing of these smart and responsive materials. And addressing those three gaps are the 'big brunt' of this essential research area at ARL.

"All of this is a fun project and it's really exciting," Rawlett said. "Certainly it's critical, because we work for the Warfighter and it's our job to protect that Soldier. But it's also important for many of us on a personal level as well. In my case, my brother-in-law's brother is being deployed later this month. So for me, it's exciting that the things that I do within the lab protect him and his companions. My job is to make their deployment safer and bring them home to their families. It's a meaningful job. And our entire team here really enjoys that." ■

ESSENTIAL RESEARCH AREA:

THE SCIENCE FOR MANUFACTURING AT THE POINT OF NEED

By Craig Collins

There was something special about the unmanned aerial vehicle that took flight at Fort Benning, Georgia, in December 2016: Much of it was manufactured there, on the spot, according to design specifications supplied by a team from the U.S. Army Research Laboratory (ARL).

The team was there to showcase recent advances in 3D printing technology, as part of the Army Expeditionary Warrior Experiments program. The small quadcopter that flew above Fort Benning was a combination of printed (the outer shell and propeller arms) and off-the-shelf (the motor and propeller assemblies) parts.

The Army has been an early adopter and refiner of "additive manufacturing," or AM – the process of building structures by introducing material into an empty space, rather than the traditional "subtractive" process of machining parts and structures from masses of material. The most widely known method of additive manufacturing is 3D printing, and the Army has made use of it to produce parts such as washers, treads for robotic ground vehicles, valve stems for MRAP vehicle tires – and even, in the fall of 2016, nearly all of the parts for a working grenade launcher.

The big deal at Fort Benning was the process used to create the quadcopter, which the ARL team described as an "on-demand small unmanned aircraft system," or ODSUAS. The drone's computer-aided design (CAD) was created in the moment, based on specifications supplied by team members.

The demonstration of this process points to a dynamic future in which drones – or anything useful that can be created by additive manufacturing – can be created on demand, by forward-deployed units, to satisfy specific mission requirements.

■ The 3D-printed ODSUAS flies at speeds of up to 55 miles per hour. Although the lightweight shell and propeller arms are printed using additive manufacturing, the motors and propellers are assembled using off-the-shelf equipment.

PHOTO BY ANGIE DEPUYDT

U.S. ARMY PHOTO BY SPC. ROGER HOUGHTON

John Gerdes, an engineer with the U.S. Army Research Laboratory, explains the capabilities of the On-Demand Small Unmanned Aircraft System, or ODSUAS, to Soldiers at the Army Expeditionary Warrior Experiments, or AEWE, at Fort Benning, Georgia, Dec. 1, 2016.


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Imagine, for example, a reconnaissance patrol coming across a complex of buildings that must be searched, inside and out, for IEDs or enemy combatants. The unit could relay its mission requirements to the nearest expeditionary fabrication facility, where technicians configure a UAV based on those requirements using specialized design software. The final design may be, like the ODSUAS, a combination of off-the-shelf and custom printed parts, which technicians will rapidly assemble and deploy to the unit within 24 hours of its request.

It's easy to imagine that a UAV's configuration would depend on variables such as the environment – a dense jungle canopy, or a cave, or an open expanse requiring wide-area surveillance – and the purpose for which the vehicle is needed. Circumstances may require it to be armed, or to carry more sophisticated sensing equipment. The advantages of such on-demand customization are obvious: It's a cost-effective approach that gives a unit exactly what it needs to fulfill a mission, when it needs it, enabling maximum flexibility and agility in the field. For this reason, the Science for Manufacturing at the Point of Need has recently been defined as one of the ARL's Essential Research Areas (ERAs).

Additive Manufacturing: Technologies and Processes

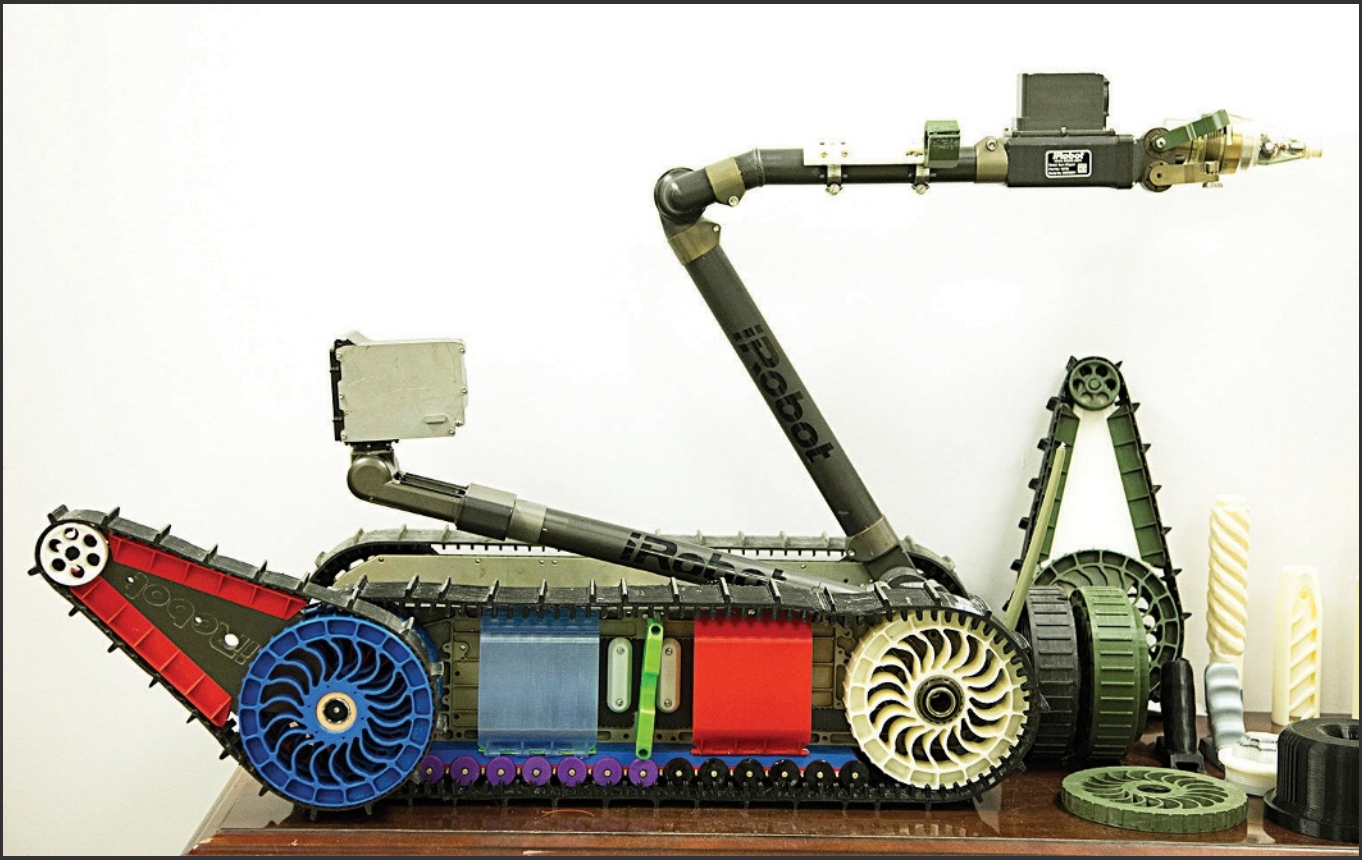
Coordinating this ERA is William Benard, PhD, an electrical engineer and senior campaign scientist for ARL's Materials Research campaign. The Army has made much progress in recent years in its explorations of 3D printing technology, but several hurdles must be cleared before the vision of on-demand tactical manufacturing can be realized.

First, the technology must mature to the point at which a wider range of material properties – strength, adhesion, conductivity, magnetism, or porosity, to name just a few – can be programmed into designs and manufactured to specifications. There are three main methods of 3D printing today:

- Material extrusion such as fused deposition molding (FDM). FDM works by uncoiling materials – plastic filaments or metal wires – and melting them to apply thin layers that build up to form a structure.
- Photo-polymerization such as stereolithography (SLA) begins with

TOP: James Zunino, a materials engineer with the Armament Research Development and Engineering Center, at Picatinny Arsenal, New Jersey, discusses a 3D printed grenade launcher during Lab Day, May 18, 2017, at the Pentagon. **ABOVE:** Most, although not all, of the parts of this grenade launcher were 3D printed.

PHOTOS BY SGT. JOSE TORRES



■ **Army PACBOT lightened by 6 pounds by using 3D printed parts (shown in color). 3D printing capability in the field means that Soldiers won't always have to wait for spare parts to arrive from original manufacturers, increasing Soldiers' readiness and flexibility.**

U.S. ARMY PHOTO BY ERIN USAWICZ

materials – typically polymers – in liquid form that are hardened by ultraviolet lasers.

- Powder-based systems such as Selective Laser Sintering (SLS) or Direct Metal Deposition (DMD). SLS starts with a bed of fine powdered materials that are melted and bonded by lasers in successive micro-layers to form a structure. The grenade launcher produced by the Army's Research, Development and Engineering Center (ARDEC) last fall involved an SLS technology that welded components out of fine powdered metal. DMD uses a nozzle to spray powder that is melted with a laser to precisely deposit material.

The variety of materials that can be printed with these technologies includes waxes, plastics, polymers and epoxy resins, as well as metals such as titanium, aluminum, steel and copper. Existing part designs cannot tolerate significant material property variability, which would be necessary to allow printing of mission-critical parts, said Benard. "The materials properties of rigid plastics, as typically printed, aren't very good, for example," he said. "The base material can perform well if you were to form something with, say, injection molding, but if you create a structure using FDM, the material's performance is poor. It has been observed that during deposition the composition of the polymer varies across the extruded bead due to thermal and flow gradients in the nozzle. Consequently, the bond from one extruded bead to another isn't very good. The interface doesn't hold up very well, and that's something people are investigating."

A number of emerging technologies promise greater control over the properties of printed metals, which are usually produced by melting powders with lasers. Recent developments include a sintering process that uses an electron beam instead of a laser to flow metal powder and melt it to produce a part. "What's interesting about that process," said Benard, "is that the newer platforms allow you to tune some materials properties such as alloy composition."

One of Benard's main points of emphasis, as he begins to outline ARL's work in this area, is the ability to understand how materials properties can by driven by the additive manufacturing process, and how those processes can be controlled to achieve desired properties. "We want to get to the state where the materials we're able to produce with additive manufacturing have better properties than we'd get from, say, conventional casting or other approaches to producing a metal part."

And that would be just a first step, he said: Many of the components he imagines producing at the point of need will require different properties at different locations on an assembly. "Additive manufacturing has a benefit of being able to produce geometries that you can't produce using conventional subtractive manufacturing," he said, "but it also has this promise that, as we drive the process control, we're going to be able to change the materials properties as a function of location within the part."

Imagine, for example, that a unit must replace a load-bearing lever arm that sits

These parts were made using additive manufacturing, which creates plastic items and other durable components by adding material, layer by layer, using 3D printers.

U.S. ARMY PHOTO

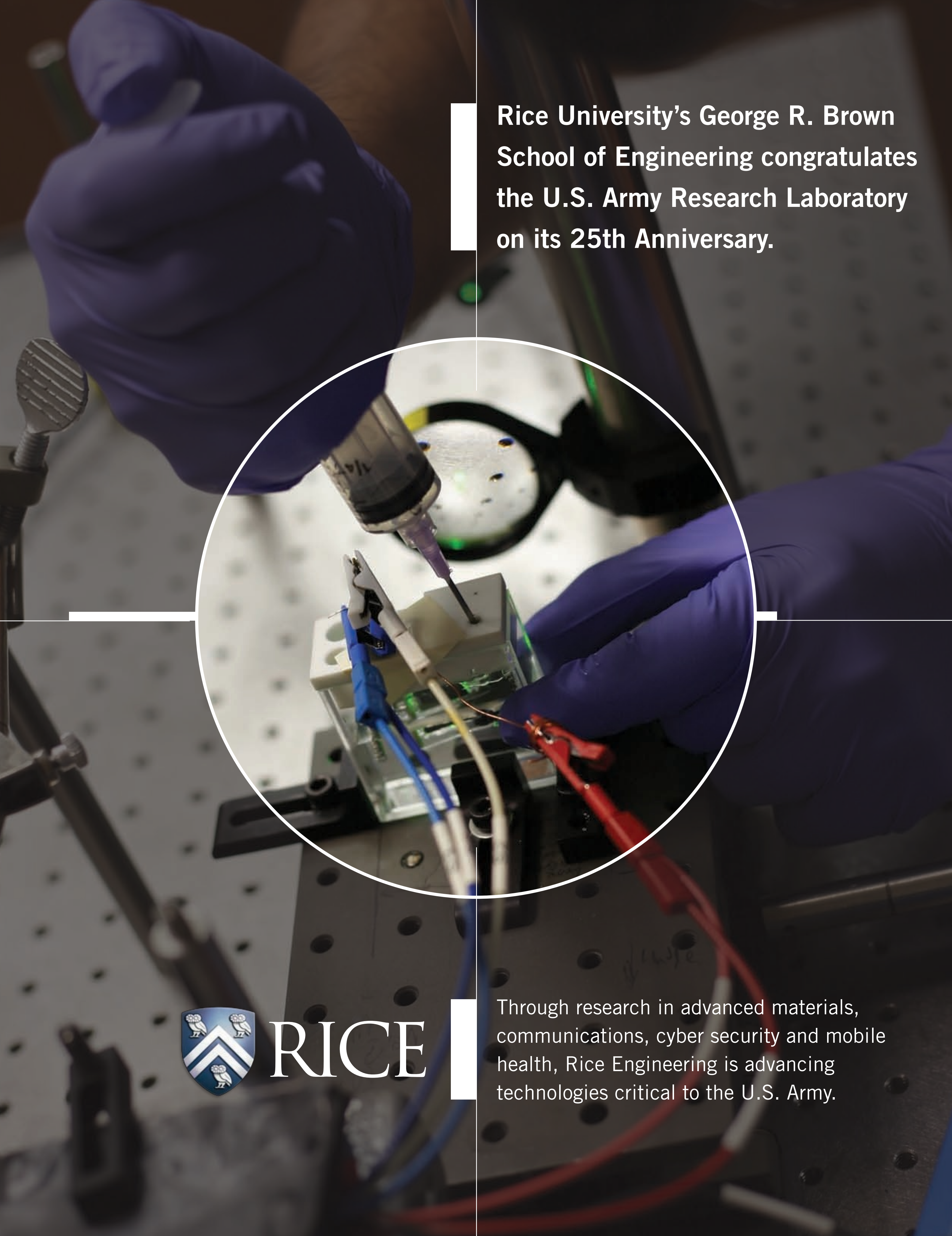
on an axle and rotates. If the material can be made harder at the bearing surface, it will wear much better on the axle; if it can be made more ductile along its length, it can ease the stress of the load. "You could have a nice robust part that has the properties tailored for high performance within a single material – you wouldn't need as much material to serve the same function, so you achieve a much lighter-weight part," said Benard.

Another advantage of AM over conventional manufacturing is the ability to add functionality – and multi-functionality – to a part. Increasingly, 3D printing isn't merely appropriate for printing structural parts; researchers have produced functional parts. Batteries, for example, have been printed by laying down fine layers of lithium ions and, more recently, graphene.

Embedding functionality within a part – for example, printing electrical traces into armored structures – could conceivably be achieved more easily in additive manufacturing applications. "And if you want to print something highly compact like a micro-UAV," Benard said, "it would be much lighter weight, and you wouldn't have to worry about the assembly issues of running the wires, because the wires are printed into the structure. You snap it together and it will be electrically functional. It will just go."

Of course, much of an automated machine's functionality comes from its processing power. The standard CMOS (complementary metal oxide semiconductor) is a component complex enough, Benard said, that, "We won't be able to print anything with that kind of performance any time soon – and possibly ever." But one of the keys to envisioning the future of point-of-need manufacturing is the mantra "print what you can; place what you can't." Even if a forward-located fabrication lab had the capability to print a CMOS chip, printing something of that complexity would have significant disadvantages. It would be expensive, and its complexity and specialization would work against the principle of flexibility, simplicity and readiness inherent in the entire concept.

As an example, Benard cites the laboratory's recent work in printing "structural batteries" – sturdy vehicle frames, for example, that could both provide rigidity and store energy, without the additional weight of an add-on battery. "But you'd have to be careful with the design from a maintenance


Rice University's George R. Brown School of Engineering congratulates the U.S. Army Research Laboratory on its 25th Anniversary.
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perspective," he said, "because once the battery's reached its cycle life, you'd have to replace the structural members. It's still a useful concept – it would have to be a modular frame in which the battery section can be replaced. You don't want to arbitrarily embed everything everywhere, because it drives your cost and complexity significantly."

Rather than developing the capability to print perfectly integrated, specialized machines, Benard said, ARL is focusing on adaptability. In the future, he envisions an AM scheme where specificity is created by software, rather than parts; fabrication technicians can embed chips or batteries into a structure that has traces printed into it, which in turn will conduct data or power to components such as propellers, sensors or LED lamps. "We have platforms that can do that already," he said.

Unanswered Questions

As platforms and processes mature for fabricating printable materials into functional structures, the ARL is refining its vision of the future, navigating a "middle way" to achieve optimal customization and timeliness.

Just as Benard cautions against designing structures that are too specialized, he also realizes the primary risk inherent in a manufacturing platform capable of producing nearly limitless configurations: It's a platform that can allow you to produce something without knowing how your product is going to perform. If a technician designs a support armature that's too long for its width, the technician is risking failure. Printed ammunition will have to be carefully formulated, to meet the same safety requirements as conventionally produced munitions.

As it develops its point-of-need manufacturing capabilities, ARL will need to establish standards and best practices. "You want to be able to pick an outcome and be confident that what you print will produce that outcome," Benard said. "So you're not just going to open it up and say to the Soldier, 'Okay, here is the CAD, modify it how you see fit.' You have to have all the intelligence built into that platform, so that a relative novice will be able to use it and still have high confidence in the result."

Another issue in designing an AM scheme for the future is to refine logistics in a way that doesn't over-interpret the phrase "point of need." 3D printing and other AM methods require specialized equipment and raw materials that could bog down a tactical unit as much as any fuel tanker truck. ARL is exploring the potential for recycled and locally sourced materials to be processing into feedstocks to further unburden the logistics chain. A wide range of materials are considered probable candidates, including empty water bottles, battlefield scrap, local vegetation, sand and even MRE food waste and packaging.

Most likely, the fabrication labs of the future will look much like today's experimental mobile laboratories, including the Army's Rapid Fabrication via Additive Manufacturing on the Battlefield system, or R-FAB, which is essentially a standard shipping container modified to accommodate specialized equipment and inventories. Strategically located R-FABs could serve as depots or nodes of distribution, keeping some parts on hand and fabricating others as needed. "The point of need," Benard said, "can also be the depot."

The advantages of this scheme over a conventional logistics chain – which can still take several weeks, for example, to supply a single part for a deployed Humvee – are obvious: If something breaks down, the ability to print a part on demand from a forward-deployed R-FAB means the Humvee can be back up tomorrow. "That means I don't have to send as many Humvees into the field," said Benard, "because the reliability or the uptime of the Humvees is improved by having rapid access to parts."

This more flexible logistical chain will allow the Army to maintain just-in-time inventories of specialized parts. "If we can move to a place where Army-unique items are produced by additive manufacturing," Benard said, "that is a significant improvement, because the volumes we produce of some of these items – such as gun barrels, for example – aren't very high, and the materials and processes are very specific." Instead of contracting for, and filling a warehouse with, thousands of gun barrels, and then drawing from that inventory over a period of years, the Army can send specifications out to its flexible modular network of fabrication cells and produce them on demand. "It will involve much lower costs," said Benard, "and allow us to be more responsive. If there's a change in design, we won't be just throwing out tons of outdated inventory."

For viewers of *Star Trek: The Next Generation* who, more than 20 years ago, watched Captain Picard order Earl Grey tea from the replicators aboard the starship *Enterprise*, the future envisioned by the ARL might not seem too implausible: It might involve a suite of wearable sensors that can measure an expeditionary Soldier's precise nutritional needs, and then relay that data to an expeditionary food printer that hasn't been invented yet, for the creation of something that would supply exactly what the Soldier needs. This and many other applications – printed textiles, electronics, and even biogenetic materials – remain to be explored by the Army.

For now, Benard said, ARL's focus is on refining materials and processes, and gradually developing more sophisticated designs that move beyond merely specifying geometries. "Integration of different printing processes is one of the key areas we'll be looking at," Benard said. "It gets extremely complex. If you have a process to print a battery, that doesn't necessarily mean it's compatible with the other processes that are going to print the rest of your system." New materials – and new combinations of materials, or materials with different properties in different locations – are going to require new design rules and design tools.

"You really want to have artificial intelligence in your design software," said Benard, "to help you optimize these combinations, because the level of complexity is now extraordinary. That will be a big part of effort as we move forward: one, driving the development of the AM process and getting that extra resolution and understanding out of it. And second, learning what we need to have in these design tools to really benefit from these expanded capabilities."

Additive manufacturing at the point of need will give the Army the opportunity to create materials that have never existed before, and to tailor those materials to meet the needs of Warfighters in a specific space and set of circumstances – the ideal materials and equipment, in the right place at the right time. "It's exciting to think about a future in which we can help the Warfighter manage risk," Benard said, "by offering flexibility, alternatives and options." It's a future that may be closer than many people think – and ARL is leading the way toward it. ■

ESSENTIAL RESEARCH AREA:

ACCELERATED LEARNING FOR A READY AND RESPONSIVE FORCE

By Craig Collins

In the early 21st century, shortly after the United States Department of Defense (DOD) had committed its forces to conflicts in both Afghanistan and Iraq, the Office of the Joint Chiefs of Staff released a National Military Strategy in which the authors identified three key aspects of the security environment:

1) A wider range of adversaries, from states to non-state organizations and people, many of whom seek to disrupt international order with asymmetric, innovative means that may target civilians and symbolic locations.

2) A more complex and distributed battlespace. Today's battlespace, the authors wrote, comprises the homeland, critical overseas regions, and "the global commons of international airspace, waters, space, and cyberspace." U.S. forces will operate in widely diverse locations, from densely populated urban centers to remote, austere locations. "Military operations in this complex environment," the authors warned, "may be dramatically different than the high-intensity combat missions for which U.S. forces routinely train."

3) Technology diffusion and access. A wide range of sophisticated technology and weaponry is becoming increasingly available. Relatively inexpensive, often commercially available technologies are improving the destructive capabilities of state and non-state actors, enabling them to locate and attack targets in the United States and abroad.

To sum up: More people are doing more complicated things, more quickly, in more places, to threaten U.S. security interests. Individual warfighters will have to respond to these conditions rapidly, often in unfamiliar circumstances and environments, to meet mission objectives and avoid mistakes. "Joint Vision 2020," the doctrinal document released by the DOD in 2000, identified this capability – "decision superiority," the ability to make better decisions faster than one's adversaries – as a critical characteristic of the future joint force.

■ Spc. Stephen House, 1st Battalion, 35th Infantry Regiment, 1st Armored Division, scrolls through menus to gather the latest data sent to him on the Nett Warrior system. The new handheld device would add additional situational awareness to the battlefield and was being evaluated during Network Integration Evaluation 13.1. A pervasive learning system will need to augment a Soldier's attentive powers, rather than distract from them, as a smartphone application might.

U.S. ARMY PHOTO BY SGT. BENJAMIN KULLMAN

A U.S. Army Soldier simulates driving a High Mobility Multipurpose Wheeled Vehicle during convoy training for annual training at Fort Bragg, North Carolina. While simulations are effective training tools, a pervasive learning system would follow a Soldier throughout training and deployment.

U.S. ARMY PHOTO BY SPC. LISA VELAZCO

The Army Research Laboratory (ARL) has aimed one of its Essential Research Areas – Accelerated Learning for a Ready and Responsive Force – at helping individual combatants learn what they need to learn, when they need to learn it, for decision superiority. Like the ARL's other Essential Research Areas, it seeks to implement technology solutions to solve a particular problem – in this case, according to Kelvin Oie, PhD, the ARL cognitive neuroscientist who is coordinating the Accelerated Learning ERA: "How do we provide training that can shorten the time to proficiency in a particular warfighting skill, and then shorten the time to expertise as well?"

One way to look at the challenge facing the multidisciplinary team of researchers involved in the ERA, Oie said, is to consider that, as the security environment becomes more complex, less bound by space and time, traditional modes of military training haven't changed much. The fundamental unit of training delivery, the drill instructor, pushes a Soldier through the paces and offers feedback to achieve required levels of proficiency – and then the Soldier goes out into the world.

Soldiers in the future force will increasingly encounter things they've never seen before. "When I get out of that training environment and I go into the real world and I start to do things on my own," Oie said, "who, or what, is giving me that feedback?"

There is, for the most part, no shortcut to expertise; the learning involved is resource- and time-intensive. But the right tools – systems that deploy with the Soldier, offer pervasive opportunities for learning across a variety of tasks and domains, and supply appropriate and timely feedback on performance – could help supply that expertise where it's needed.

"If I had a system that could assess the world, decide what I need to learn about a particular task, deliver that training, and offer feedback, I could take advantage of the learning opportunities that present themselves to me in the real world, accelerate my learning, and make that learning more appropriate and targeted to what I need," said Oie.

■ **LEFT:** U.S. Army Sgt. 1st Class Brandon Hatchell, a military police platoon sergeant assigned to Multinational Battle Group- East, communicates with his platoon conducting virtual simulated training on Camp Bondsteel, Kosovo. ARL is working toward developing a pervasive learning system that would serve a function of a drill instructor or coach, looking "over the shoulder" of the Soldier and offering vital information where appropriate. **RIGHT:** Long-term studies of individuals, such as the yearlong study of astronauts Scott Kelly and Mikhail Kornienko aboard the ISS, will aid development of a pervasive learning system.

U.S. ARMY PHOTO BY CAPT. RACHAEL JEFFCOAT, 20TH PUBLIC AFFAIRS DETACHMENT

NASA PHOTO

Technologies for Pervasive Learning

As ARL scientists begin to conceptualize such a system, they're making an important distinction – they're not just looking to develop a system that will train Soldiers in specific tasks or isolated skill clusters in a particular environment. They're looking for a system that will be pervasive throughout a Soldier's life, and that has the capability to identify and deliver training-relevant feedback when opportunities arise in the context where they're needed. The feedback offered by this system would be appropriate, timely, and aimed at reinforcing what a Soldier needs to learn to become an expert.

Such a system would, in many ways, serve the function of a drill instructor or coach, but would come along for every waking moment of a deployment – though interacting selectively, when it's safe and appropriate to do so. When a Soldier enters an unfamiliar environment, the system would sense what the Soldier sees and hears. In strange surroundings, different from the world he knows or has trained for, a newcomer often doesn't know where to look. He won't be able to recognize features that may pose a threat. The system could also draw from the experiences of other Soldiers and their systems, who may have already built up their knowledge of that environment, thus helping to speed a newcomer's learning.

"Let's say a patrol is going through a marketplace that was crowded the day before," Oie said, "but on this day there aren't so many people there; there's almost nobody. Do the Soldiers know why that's occurred?" The patrol might perceive it as a threat – but if the learning system can draw upon previously gathered cultural knowledge from a common database, it might be able to offer an alternative and perhaps non-threatening explanation: Maybe it's a holiday, or the hour for a prayer service. "If a Soldier had just come into the country," said Oie, "he might not know any of that."

It may seem paradoxical to try to solve one of the challenges identified in the Joint Chiefs' National Military Strategy – the diffusion and proliferation of technology – with an additional layer of sophisticated tech wizardry. But the whole point of the pervasive learning system will be that, unlike many technological solutions, such as the dashboard GPS navigators that have been implicated in numerous accidents, it will be designed to harmonize with, rather than confound, the human brain. It will need to know, from its own reading of a given situation, whether inserting itself into a situation will risk more harm than good (causing anxiety, for example). It will need to be built to augment a Soldier's attentive powers, rather than distract from them – in the way that, say, a smartphone app might, as the Soldier takes her eyes off the scene (for example, the marketplace mentioned previously) in front of her to type a query into a personal electronic device.

For several obvious reasons, such a learning delivery system is a major stretch goal, a moon shot that's at least 20 years from being realized. For one thing, it will require a sophisticated wearable high-resolution interface far more capable than Google Glass, the optical head-mounted display recently prototyped by Google. The interface will have to be a ubiquitous computer, offering live virtual training simulations fully integrated into the Soldier's real-world environment. It will require hardware/software integration for mixed or virtual reality experiences that emerge organically from – and merge organically with – the Soldier's current experiences.

The most significant determinant of when the Army might be able to deploy such a system is the artificial intelligence needed to create a "virtual coach" that can interact with the Soldier immersively, taking account of his previous experiences, recognizing and making the Soldier aware of what he doesn't know, providing feedback and reinforcing previous learning when opportunities arise, and knowing when to keep its "mouth" shut.

"That's one of the most important challenges underlying the Accelerated Learning ERA technology goals," Oie said. "It's only a part of it – but it's the hard part. The artificial intelligence aspect is likely the most aspirational idea behind it."

Full-Spectrum Instruction

The marketplace example illustrates the interaction of different domains: In this case, cultural awareness (knowing all the reasons the marketplace might be empty)

informs tactical intelligence and readiness. "One of the things we hope to achieve with this system," Oie said, "is to take advantage of the interdependencies across different tasks. If I can give you feedback that helps you discriminate between two different conditions, you'll learn faster and you'll learn more, because you can apply this in multiple places and situations."

The big challenge here is that there are very few teaching/learning environments that encompass the complexity of this full spectrum of interdependencies. Training can get a person ready for a certain level of performance – but people tend to learn in controlled environments, from well-known examples. Some elements of that learning environment might be familiar out in the world, but many won't be. Complex decision-making, or decision-making amid uncertainty, is difficult to teach precisely because it's difficult, if not impossible, to anticipate the combination of circumstances a learner will confront.

Oie uses the example of his experience as a college volleyball player, when he learned that intensive training in one particular skill – passing, setting, or spiking, for example – was of limited use, and could even impact performance negatively when it wasn't accompanied by practice in using those skills together in game-like situations. Indeed, research in motor learning and skill acquisition has shown that focused practice (performing a certain skill repeatedly) is good for mastering specific situations, but random practice (playing the game) is the best learning mode for transferring that skill to the real world. Educational researchers know this happens, but they don't know exactly how it happens, which is a necessary step toward building a system that will assist in this transfer.

"We're really grappling with the actual complexity of the world our Soldiers have to face," said Oie. "Part of what makes it so challenging is because the models and the approaches that we use to drive things like artificial intelligence, at this point, haven't been able to fully deal with that kind of complexity either."

To return to the crowded marketplace: The pervasive learning system of the future wouldn't be designed to interact with a Soldier on patrol who needs to be focused on staying alive and meeting mission objectives. But it might help the Soldier recognize the empty marketplace as a safe environment, and might even be able to take the opportunity to provide more training. It could then provide full-spectrum instruction amid a virtual re-creation of a crowded marketplace, replete with virtual characters interacting in the existing space, each requiring an assessment and reaction from the Soldier, whose decisions could be probed and evaluated by the system.

Adaptive and Augmentation Systems and Tools

Another key research area for development of a pervasive learning system will be the ability to adapt not only to variability among individuals – their different histories and levels of knowledge, skill, and receptivity – but within individuals as well. In order to arrive at the optimal decisions about what to teach, and when, and how, a system will need to get an accurate reading of what's known in some pedagogical circles as the "learner state" – the combination of mental, physical, and emotional factors that may affect a person's ability to learn at a given moment. If a person is tired, or stressed, or hungry, for example, she may not be as ready to hear a lecture as when she is well rested, more relaxed, and not distracted by hunger.

The Army has developed an open-source, computer-based tutoring system – the Generalized Intelligent Framework for Tutoring (GIFT) – that allows instructors to design, and individuals to receive, instruction tailored to their needs. GIFT is a software framework informed by a sensor module, which processes and stores user data from inputs and sensing technologies, such as a wrist sensor that detects physiological changes; a domain module, which provides content, assesses performance, and provides feedback; and a trainee module, which is essentially a database of historical and sensor data that processes a trainee's cognitive and affective needs.

The future system will require a more generalizable intelligence, Oie said, fueled by advanced models of "intra-individual" variability over time. "The scientific community hasn't looked as strongly at intra-individual variability," he said. "Part of that is simply practical. Recording one person for a very long time under controlled situations isn't really possible in most contexts." Recent exceptions involve sleep studies or the yearlong studies, from March 2015 to March 2016, of astronauts Scott Kelly and Mikhail Kornienko aboard the International Space Station. These examples illustrate a growing trend in the human sciences, and the proliferation of wearable sensing technologies has opened new possibilities for the community in tracking user states over long periods of time.

"In pretty loose terms," Oie said, "there is the pedagogical approach: 'How do I teach?' The instructional method is: 'What do I teach?' And then the human variability model is: 'How do I adapt that instruction to the individual at this time?' If you can put all those together into this intelligent framework, you're starting to get to the kind of teaching or training capability we'll need in the future. But there's a lot of research that needs to be done in order to get there."

One of the distinguishing features of the "point of need" learning that ARL hopes to deliver with its future system is that it will have to happen quickly – and from what we know about intra-individual variability, being ready for learning isn't always likely. Another area of exploration for ARL researchers is augmentation tools – methods and mechanisms for improving learner states to enhance the impact of training.

There's a wide range of such tools available, and there is some evidence suggesting they work – neurofeedback, for example, a type of biofeedback that measures brain waves to produce a signal that a person can use to self-regulate. Another approach the group is examining is mindfulness training or meditation, which has been shown to be a proven tool for boosting cognition and performance in other applications.

It's not clear in many cases how these mechanisms work and what their real-world impact will be, but these are questions the Accelerated Learning group will be studying in the years to come. "The extent to which these can put you into a better state, or allow you to better control your states," Oie said, "is something we could be looking at. We're hoping for better insights into how the brain and body interact to improve capability." Once those insights arrive, along with systems intelligent enough to put them to work, look for Soldiers to be taking a wealth of wisdom and knowledge – more than possibly could be contained within a single warrior – into battle with them. ■

ESSENTIAL RESEARCH AREA: DISCOVERY

By Scott R. Gourley

Unlike the other Essential Research Areas (ERA) identified by the U.S. Army Research Laboratory (ARL), the "Discovery" ERA does not focus on a specific area of research, but rather provides critical underpinnings for science and technology broadly. For specificity, Discovery has been framed with five Exemplars.

"We consider Discovery underlying," offered Peter Reynolds, PhD, and lead for the Discovery ERA. "Discovery is at the base of all the ERAs."

"Discovery is the source of the scientific ideas and insights that underlie all future science and technologies," he explained. "It is through Discovery that we prevent technological surprise. A potential adversary has the same access to nature that we do; they can do the same experiments and the same theoretical studies. We don't want to get into a situation where an adversary can do this better or faster, because then they'll make crucial discoveries before we do. As examples, we were first to discover the underlying science that led to things like the laser and nuclear weapons. Those are just two examples of where we have the advantage today because we created technological surprise instead of being taken by surprise."

In recognition of these realities, work performed under the Discovery ERA is summarized as "seeking to identify, create, develop and exploit innovative Army-critical scientific discoveries that are crucial for the Army's future technological superiority; create technological surprise for our adversaries; and avoid technological surprise for ourselves."

"That's the key," Reynolds said. "That's really what we are all about."

Reynolds noted that the organization within ARL whose mission is primarily focused on Discovery, the extramurally oriented Army Research Office (ARO), predates ARL, going back to 1951. ARO became part of ARL much later, several years after ARL was formed.

"We support the creative, Army-relevant work of the brilliant minds in the university community. We help guide these ideas, and we focus them to where we can see the long-term potential Army-relevant applications," he said. "In fact, it was our funding in the 1950s that led to the laser."

Reynolds related how the concept of Department of Defense (DOD) funding agencies grew out of Vannevar Bush's wartime Office of Scientific Research and Development and his subsequent report "Science, the Endless Frontier" commissioned by President Franklin D. Roosevelt in the aftermath of World War II. Congress formalized this newly recognized need for national investment in basic research as the Office of Naval Research (ONR). ARO and the Air Force's counterpart (the Air Force Office of Scientific Research, or AFOSR) were formed subsequently, as it was recognized by all the services that basic research was critical to their future technologies. "Believe it or not," said Reynolds, "the National Science Foundation also came as a result of this wartime report, and was modeled directly after the Navy's ONR."

Today, the research conducted at and sponsored by ARL is carried out in close cooperation with the other services as well as outside research entities and academic entities.

"We're looking for the innovations within different areas that are of potential relevance to the Army and that are also breakthroughs," Reynolds said. "But it's not just a question of the relevance. It's also a question of whether there is a scientific opportunity. What's the reason to think that a breakthrough is possible now?"

He illustrated the point with the notional example of *Star Trek*'s "transporter," posing the question, "If I could have anything I wanted for a future Army, why wouldn't I invent a transporter like in *Star Trek*? Then, instead of having all the logistics burden and requirement to transport everything to and around the battlefield, the Army could just teleport everything instead. That's certainly Army relevant."

He continued, "There is, in fact, an area of research called quantum teleportation, and you can teleport photons and teleport the quantum states of simple particles. But, would I invest in teleportation to transport our troops? No I wouldn't. There is no scientific opportunity for that. Despite quantum teleportation, which has its uses for teleporting information in quantum computers or quantum networks, there's no way forward, at least for now, to teleporting anything of real substance."

"We only invest where there's scientific opportunity, which means that the field is blossoming in a certain way," he said. "That would mean that there are breakthroughs happening in the field that show you some of the next steps. When there's both Army relevance and scientific opportunity, our program managers are there and will invest. And that causes whole areas, whole branches of science to open up."

Reynolds described the five "Exemplars" of the Discovery ERA. They encompass myriad projects being performed and planned under the Discovery ERA: Quantum Information Science; Living Materials; Topological Matter; Biophysics-Based Measuring and Modeling of Social Dynamics; and Complexity and Emergence.

Reynolds said that when the ARL ERAs were first formulated, the first step was to identify what was currently being done in each of those areas.

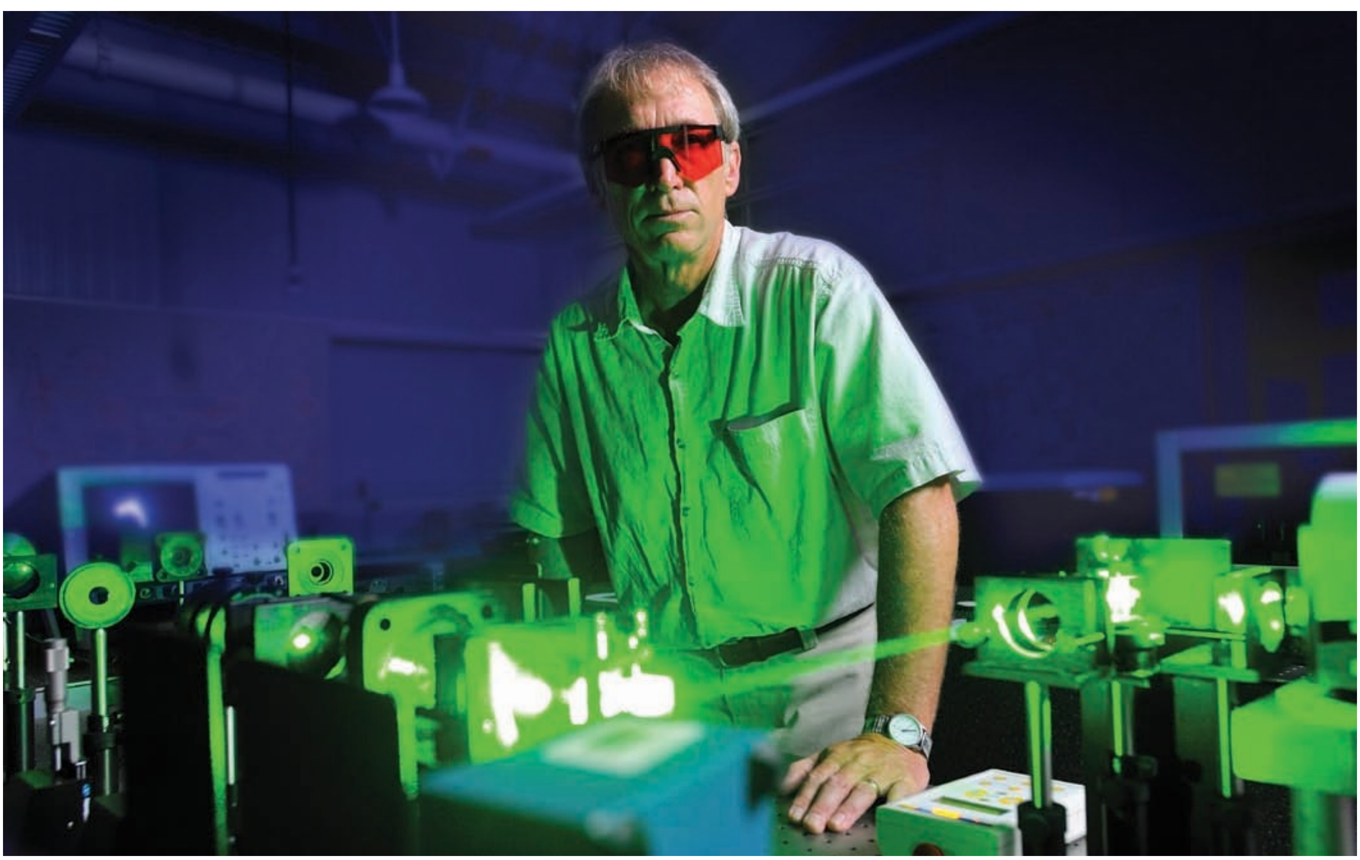
"For the Discovery ERA, we treated each Exemplar almost as an ERA in itself."

He offered the example of Quantum Information Science, noting that it exploits the "2nd quantum revolution" and targets "beyond classical functionalities in all elements of C4ISR."

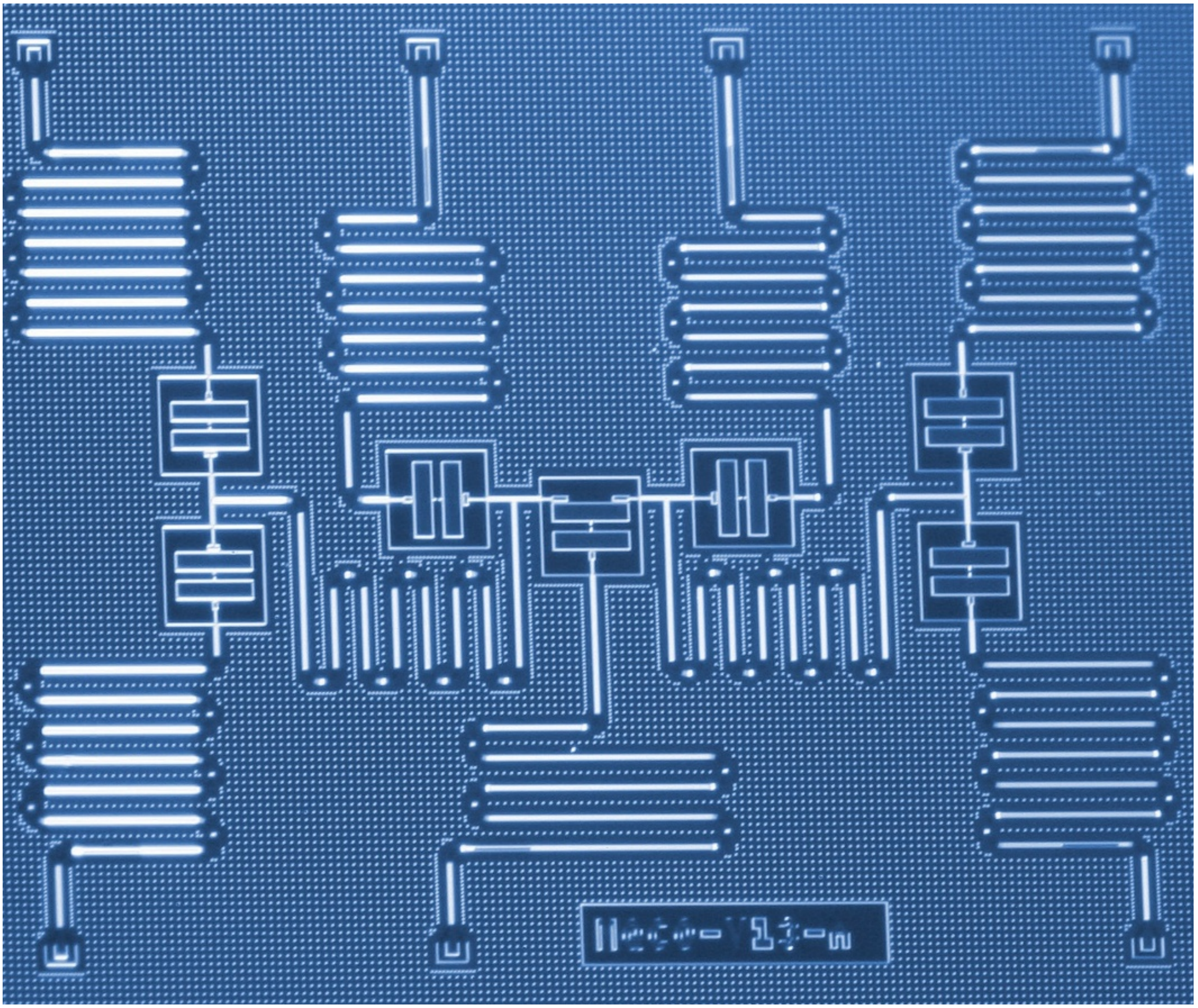
"Quantum is one of the areas that I was actually involved with 30 years ago," he began. "I had responsibility for investing in atomic physics. The outcome was new and better clocks that are now part of GPS, but as with all basic research, it also created unanticipated new avenues for research and technology. It led to the unanticipated, much broader field of Quantum Information Science, which blossomed into an area that is leading to new forms of matter, way more sensitive sensors, new forms of imaging, and communication of 'coherent, quantum information,' all of which are more powerful than anything classically possible."

Reynolds described how the gradual maturation of this new field led to the ARL in-house Quantum Networks program, based on research that started more than 30 years ago, explicit planning that started in roughly FY 11 or FY 12, and funding that began in FY 15.

A U.S. Army Research Laboratory scientist working with a laser. Lasers, so ubiquitous and vital to the world today, were developed from initial research of the underlying principles. The U.S. Army Research Laboratory's Discovery ERA is the source for the scientific ideas and insights that will lead to future science and technologies.



U.S. ARMY PHOTO BY DOUG LAFON



IBM IMAGE

■ Illustration of an IBM quantum processor. Quantum Information Science is one of the Discovery ERA's five "Exemplars."

"We proposed that there should be work in-house in quantum, based on the results being obtained from the previous 25 years of support by DOD," he recalled. "So that's how we got a program actually to begin in-house. And the focus of the in-house program is on quantum networks because that is the most clearly relevant aspect to the Army, and presented both near-term and far-term opportunities within quantum."

One of the most obvious uses for a quantum network would be for secure communications.

"The security of most everything nowadays is based on encryption, and encryption becomes vulnerable because of quantum," he said. "All of current encryption is based on what's called RSA – an algorithm based on how hard it is to factor large numbers. When you do transactions on the internet, and it says it's a secure web page, that's based on this RSA algorithm."

Reynolds explained that the RSA algorithm begins with two very large prime numbers that are multiplied together.

"Now, this bigger number only has two factors. The security is built from the fact that if you don't know those two numbers, a computer can't find them without taking up an exponentially growing amount of time. That means as I make the numbers not so much bigger, I can make it take the age of the universe for a computer to be able to find the factors," he asserted.

Reynolds observed that every computer currently used, "from high performance computers to your iPhone," operates on a conceptual design originally formulated by the mid-20th century British mathematician Alan Turing, and are broadly dubbed "Turing machines."

"You simply can't break RSA encryption with a Turing machine," he claimed. "That's the bottom line. But it turns out that quantum, this whole stuff that we were starting to invest in 30 years ago, opened up a whole new way of thinking about computing, and that, in fact, we now know can break RSA in polynomial time. If you can ever build a quantum computer, and everyone is racing to do that now, security based on RSA is gone. So everything that we've encrypted that way up until now is no longer going to be encrypted in a few years."

Reynolds said that the answer to that encryption dilemma can again be found in using quantum mechanics – not to break the encryption but to make the encryption, pointing to the new quantum networking program at ARL that will support that as one of its goals, in addition to other potential Army applications.

In the case of the Quantum Information Science Exemplar, current investments are focused in five major areas: Foundations – understanding complexity in quantum systems and quantum limits; Quantum Sensing and Precision Measurement – exploring the power of controlled small quantum systems to beat classical shot noise limits for sensing and measurement; Quantum Computing – understanding the challenges of constructing small qubit [quantum bit] systems and the algorithmic power of such systems to solve hard computational problems; Distributed Quantum Information Processing – understanding and demonstrating entanglement distributed in networks and exploring new methods of computing, communications and sensing using such networks; and New Regimes in Quantum Systems – exploring new quantum regimes reachable because of quantum control, connectivity, and strong nonlinearity in small qubit systems.

Numerous specific projects are being conducted within each of those sub-areas supporting the topic.

Along with the current investments in these topics, the ARL Discovery ERA, as with each of the other ERAs, has identified a number of "gaps."

"The 'gaps' are our vision of what are the most important things to be going after that we're not doing yet," Reynolds said. "In other words, they are the things that we can envision based on what we are doing now, that are the most important next steps that we need to be doing. We prioritized them and identified 'sub-gaps' that each serve as major research directions that could be performed by multiple teams at different institutions, both extramurally and at ARL."

The Exemplar of Living Materials focuses on the identification, characterization, and engineering of evolutionarily tuned and robust biological systems to provide the framework for radically new materials synthesis, with properties and functions adaptable to a broad range of environmental conditions.

Reynolds identified specific Living Materials project areas as employing and/or emulating biological systems toward three-dimensional directed and controlled assembly of materials, effectively transporting biological processes "outside of the cell," exploiting the ability to manipulate cellular metabolic processes toward directed and complex functions (synthetic biology) and exploiting microbial diversity to guide spatial patterning of functional community structure.

As with the Quantum Exemplar, Living Materials includes a number of ongoing projects, ranging from topics like materials with integrated biological components, and non-biological materials produced by biology, to principles of microbial community organization, structure and function, and cellular survival in austere environments. Additionally, prioritized gaps and sub-gaps provide specific directions for future research.

The Topological Matter Exemplar seeks to understand and build on recently discovered new realms of electronic and photonic matter.

Not surprisingly, as with all of science, there are connections. In this case, some of the topological properties of topological matter are anticipated to be extremely useful elsewhere. As just one example, Reynolds noted that the "protection" of certain properties due to topology is likely to be very useful in Quantum Information Science.

The three broadly identified gaps within Topological Matter include the following. First is that the role of defects and disorder in topological matter needs better understanding and control. Second, novel topological device concepts are needed. These device concepts should provide functions or capabilities that are not attainable with standard semiconductors. And third, we need better understanding and ability for exploiting next-generation topological phenomena.

In the case of Defects and Disorder in Topological Matter, for example, Reynolds pointed to identified and prioritized research sub-gaps involving: The study of defects at the surface of topological materials and at their interface with other functional materials, including defect mitigation schemes; development growth technique for pristine defect/disorder-free materials, both bulk and epitaxial, such that topologically non-trivial phenomena are readily observable at room temperature; and investigation of defect-stabilized topological states such as the quantum anomalous "Hall effect" resulting from dilute magnetic doping of a topological insulator.

The fourth Discovery exemplar involves Social Dynamics. By studying the emergence of group behavior – as different from individual human behavior – ARL researchers hope to provide future warfighters with situational awareness of emerging conflict "hotspots," improved capacity to identify potential allied and adversarial groups, methods of detecting intergroup conflict, and tools to enhance cultural competence without heavy training requirements focused on specific cultures.

Both ARL in-house research and ARL/ARO extramural research efforts focus on related areas such as Social Biometrics, Population Modeling and Prediction, and Measuring and Modeling Cross-Cultural Dynamics.

The final Discovery exemplar is Complexity and Emergence, which Reynolds described as "a broad and crosscutting realm across multiple Army concerns in complex environments."

Specific areas of research impacting on Complexity and Emergence include network science, complexity science, new mathematical strategies and techniques, critical phenomena and phase transitions, non-equilibrium behavior of systems, searching for underlying physical principles, understanding information exchange and its control, working with big data, uncertainty quantification, optimal verification and validation, and studies of emergence.

Reynolds reiterated that the Discovery research activities target "far future" benefits to the Army.

"To some extent, of course, we are supporting today's warfighter, because basic research will definitely solve problems for them," he said. "But mostly our mission is to be looking to solve problems for the warfighter of 2040 to 2050. We're not looking at the next Army, but the one beyond that, because the next Army, the next generation of the Army, is going to be using technologies where the discoveries have already been made. That's the stuff that's been discovered in the last 10 to 20 years. It's already out there in scientific publications; and it's now, or soon will be, starting to be developed and engineered. This will turn into products and technologies over the next decade or two. That's not what we do. We're not after the engineering of already discovered things. We're about the discovery itself, of the new science. We're that underlying discovery. We're after the Army after next." ■